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Abstract

Fast radio bursts (FRBs) exhibit a wide variety of spectral, temporal and polarimetric properties, which can unveil clues into their emission physics and propagation effects in the local medium. FRBs are challenging to study at very high time resolution due to the precision needed to constrain the dispersion measure, signal-to-noise limitations, and also scattering from the intervening medium. Here we present the high-time-resolution (down to $1\ \mu\text{s}$) polarimetric properties of four 1.7-GHz bursts from the repeating FRB 20180916B, which were detected in voltage data during observations with the European VLBI Network. In these bursts we observe a range of emission timescales spanning three orders of magnitude, the shortest component width reaching $3\text{--}4\ \mu\text{s}$ (below which we are limited by scattering). We demonstrate that all four bursts are highly linearly polarised ($\geq 80\%$), show no evidence for significant circular polarisation ($\leq 15\%$), and exhibit a constant polarisation position angle during and *between* bursts. On short timescales ($\leq 100\ \mu\text{s}$), however, there appear to be subtle (few degree) polarisation position angle variations across the burst profiles. These observational results are most naturally explained in an FRB model where the emission is magnetospheric in origin, as opposed to models where the emission originates at larger distances in a relativistic shock.

1 Introduction

Fast radio bursts (FRBs) are bright (fluence $0.1\text{--}100\ \text{Jy ms}$), coherent, short-duration ($\mu\text{s}\text{--ms}$) radio transients of as-yet unknown extragalactic origin (for recent reviews, see [1,2](#)). Studying FRBs with high time and frequency resolution, as well as full polarimetric information, is crucial for understanding their emission physics, and also probes potential propagation effects in their local environments.

Some FRB sources have been observed to produce multiple bursts (e.g. [3,4](#)). Whether there is a difference in the physical origin of repeating FRBs and apparently non-repeating FRBs is currently debated — though the high volumetric occurrence rate of FRBs suggests that most are capable of repeating⁵. While apparent non-repeaters can now also be precisely localised and associated with their host galaxies⁶, actively repeating FRBs are particularly rich sources for follow-up: e.g., searching for low-energy bursts with sensitive radio telescopes to study the energy distribution (e.g. [7](#)), searching for bursts at a wide range of radio frequencies to study their spectral properties (e.g. [8,9](#)), and using long-baseline interferometers to precisely localise the bursts and thereafter perform multi-wavelength follow-up to identify and study the host galaxy and local environment^{10–14}. The repetitive nature also provides the opportunity to target these sources and record voltage data for multiple bursts — in order to probe very high time and frequency resolution, and study the polarimetric properties over a wide range of observing epochs and radio frequencies.

Many FRBs show complex burst morphology and, to date, both repeaters and apparent non-repeaters have shown temporal structure, ‘sub-bursts’, as short as $\sim 20\text{--}$

$30\ \mu\text{s}$ ^{15–17}. In the case of FRB 20181112A¹⁷, the observations are limited by scattering. Probing even shorter, $\sim 1\ \mu\text{s}$, timescales is a powerful way to constrain emission models because of the limits that such temporal structures place on the instantaneous size of the emitting region: $1\ \mu\text{s}$ corresponds to $300\ \text{m}$, though special relativistic effects cause the light-travel size to be much smaller than the actual size.

The recent discovery of an exceptionally bright ($\sim 1.5\ \text{MJy ms}$) burst from the Galactic magnetar SGR 1935+2154^{18,19} provides a strong argument that at least some extragalactic FRBs have a similar origin. However, both theoretical models for radio burst emission in the magnetosphere (e.g. [20](#)) and much further from the neutron star in a relativistic shock (e.g. [21](#)) have been proposed. Arguably, shorter timescales are more naturally explained in a magnetospheric scenario compared to a shock model.

Voltage data allow access to such timescales, but several practical challenges remain: e.g., scattering due to multipath propagation can limit the effective time resolution (especially at low radio frequencies); the signal-to-noise (S/N) on short timescales may be too low; there may be limitations on the precision with which the dispersion measure (DM) can be determined, such that it is impossible to ensure that the DM smearing is less than the time resolution; and, if the bursts are composed of a forest of closely spaced (sub-) μs sub-bursts, then confusion may limit our ability to identify individual structures.

Ultra-high-time-resolution studies are even more powerful if they include full polarisation information. In general, FRBs show a wide variety of polarimetric properties. FRBs have been observed to exhibit linear polarisation fractions ranging from $\sim 0\%$ to $\sim 100\%$ (see e.g. [16,22–24](#)). Some FRBs show significant circular polarisation (e.g. [25](#)), though most so far show very little (e.g. [23,26](#)). Some sources show flat polarisation position angles (PPA) across the burst profile^{4,16,24}, whereas others show a PPA variation (e.g. FRB 20110523A²²), where the PPA is defined as the angle of orientation of the electric field plane referenced at infinite frequency.

When FRBs propagate through a magnetised cold plasma, the magnetic field component parallel to the line-of-sight, $B_{\parallel}$, induces so-called Faraday rotation of the linear polarisation vector. This effect is quantified using the rotation measure,

$$RM \equiv \frac{e^3}{2\pi m_e^2 c^4} \int_d^0 B_{\parallel}(l) n_e(l) dl, \quad (1)$$

where e is the electron charge, m_e is the electron mass, $n_e(l)$ is the total electron density at a distance of l from the observer, c is the speed of light, and d is the distance to the source. FRBs show RMs from $\sim 10\ \text{rad m}^{-2}$ to $\sim 10^5\ \text{rad m}^{-2}$, spanning four orders of magnitude^{16,26,27}. In some cases, the RM is too high to be explained by the Galactic foreground, and indicates that the local environment of the FRB dominates (the contribution from the intergalactic medium is negligible).

The polarisation properties of FRB 20121102A, the first discovered repeating FRB^{3,28}, were measured at $4\text{--}8\ \text{GHz}$ with Arecibo¹⁶ and the Green Bank Telescope (GBT)²⁹. FRB 20121102A bursts are $\sim 100\%$ linearly polarised, and

show no sign of circular polarisation. There is evidence of a linear polarisation decrease towards lower frequencies but whether this is intrinsic or reflects a propagation effect is currently unclear (Plavin et al., in prep.). Additionally, for FRB 20121102A, the PPA is flat across the burst duration, and the absolute value of PPA is approximately equal between bursts¹⁶. The RM of FRB 20121102A was found to be very large ($\sim 10^5 \text{ rad m}^{-2}$), and highly variable (variation of $\sim 10\%$ over 7 months), implying an extreme and dynamic local magneto-ionic environment^{16,30}.

FRB 20190711A has recently been shown to repeat^{24,31}. As with FRB 20121102A, the bursts also show high fractional linear polarisation ($\sim 80\text{--}100\%$), no significant circular polarisation, and a flat PPA across the burst profile. The RM of FRB 20190711A was found to be $9 \pm 1 \text{ rad m}^{-2}$, four orders of magnitude smaller than in the case of FRB 20121102A.

The only other repeating FRB with published polarisation information from multiple bursts is FRB 20180916B^{4,32}. The RM measured for FRB 20180916B is three orders of magnitude smaller than what is seen for FRB 20121102A ($-114.6 \text{ rad m}^{-2}$)⁴. CHIME/FRB Collaboration et al.⁴ discuss the capture of CHIME/FRB voltage data during one burst from FRB 20180916B in the frequency range 400–800 MHz. With this data, measurements of the polarisation fractions and RM were first possible. This burst exhibits $\sim 100\%$ linear polarisation, and shows no evidence for circular polarisation. The PPA appears to be flat over the burst duration. The polarimetric properties of four bursts from FRB 20180916B, detected at 300–400 MHz using GBT, were presented in Chawla et al.³². They report the same polarisation properties as the original discovery ($\sim 100\%$ linear, flat PPA, comparable RM) supporting the idea that repeating FRBs have consistent polarisation properties between bursts from the same source, and that the phenomenology is potentially consistent between different repeating FRB sources.

FRB 20180916B’s polarimetric properties have not previously been investigated at radio frequencies $> 1 \text{ GHz}$, where most FRB 20121102A studies have been conducted, and previous studies have been limited by the temporal resolution of the data. It is unclear if the polarimetric properties seen from FRB 20180916B at 300–800 MHz persist at higher radio frequencies, and the shortest temporal structure reported to date is $\sim 60 \mu\text{s}$ ¹⁴. Also, at higher frequencies, measurements of the PPA are less affected by RM variations as a result of propagation effects, and thus variations in the PPA are easier to study. Here we present an analysis of four 1.7-GHz FRB 20180916B bursts whose spectro-temporal properties were previously presented¹⁴. In the present work, we provide a higher-time-resolution, full polarimetric analysis of this sample. Throughout this paper we use the nomenclature B_n for the four bursts (ordered according to their arrival time, i.e. B_1 arrived earlier than B_2), matching the nomenclature used in Marcote et al.¹⁴. Additionally, we introduce the nomenclature $B_4\text{-sbn}$ for the three clear sub-bursts in burst B_4 (see Figure 1 in Marcote et al.¹⁴, or Figure 4 in this work). In §2 we present the high-time-resolution analysis and results. In §3 we present the polarimetric analysis and results, and thereafter discuss

the consequences for our understanding of FRBs in §4.

2 High time resolution data, analysis and results

In our previous spectral and temporal characterisation of these bursts¹⁴, we found that B_3 and B_4 show several sub-bursts with widths ranging from 60–700 μs ; see Table 1 of Marcote et al.¹⁴. The available (relatively limited) bandwidth of 128 MHz made it difficult to convincingly detect the downward-drifting ‘sad trombone’ effect often seen from repeating FRBs^{33,34}, but this has previously been demonstrated for FRB 20180916B at lower radio frequencies⁴. Here we probe order-of-magnitude shorter timescales by studying the burst temporal properties at higher time resolution.

The data were acquired as part of a European Very-Long-Baseline-Interferometry Network (EVN) campaign on 2019 June 19 (experiment code: EM135C) at a central radio frequency of 1.7 GHz. Using SFXC³⁵, we converted the voltage data from the 100-m Effelsberg telescope into full-polarisation (circular basis) filterbank data with time and frequency resolutions of 1 μs and 0.5 MHz, respectively. In this process, the data were coherently dedispersed to a dispersion measure (DM) of $348.76 \text{ pc cm}^{-3}$, which is the best-fit DM that maximises S/N for burst B_4 at 16 μs time resolution¹⁴. Using PSRCHIVE³⁶, we created archive files containing each burst from the filterbank files at the native time and frequency resolution. We manually mask frequency channels that are contaminated by radio frequency interference (RFI), and additionally we mask artefacts at the sub-band edges.

We refine the burst DM using the PSRCHIVE tool `pdmp` to search for the DM that maximises S/N of burst B_4 (the brightest in our sample) in the 1 μs resolution data. The DM is found to be $348.772 \pm 0.006 \text{ pc cm}^{-3}$, which is 0.012 pc cm^{-3} greater than the value the data is coherently dedispersed to. In case the burst is comprised of bright $\sim \mu\text{s}$ shots of emission, we additionally search for the DM that maximises the peak in the profile structure (using the metric of maximising (max-min) of the time series). This was found to be $348.775 \text{ pc cm}^{-3}$, consistent with the `pdmp`-determined value. We incoherently dedisperse the 1 μs data, to the `pdmp`-determined value ($+0.012 \text{ pc cm}^{-3}$).

In Figure 1, we present the four FRB 20180916B burst profiles at both 16 μs and 1 μs resolution. In the case of bursts B_1 and B_2 , the increase in time resolution does not reveal any shorter timescale structure, and the burst widths are consistent with the widths measured previously ($1.86 \pm 0.13 \text{ ms}$ and $0.24 \pm 0.02 \text{ ms}$ for B_1 and B_2 , respectively)¹⁴. Bursts B_3 and B_4 show clear structure in the 16 μs resolution data. By increasing the time resolution to 1 μs we see clear 10–20 μs structure in burst B_4 (panel k, Figure 1), and the bright component of B_4 does not appear to be a simple Gaussian envelope, but instead exhibits 10–20 μs fluctuations on top of the envelope (panel l, Figure 1). B_3 also exhibits interesting structure at 1 μs resolution in the form of 50–100 μs components (panel j, Figure 1), and even a component that is only a few μs wide

(panel i, Figure 1). We note that the two 3–4 μs components shown in panel i, Figure 1, are detected across our 128 MHz band. The 3–4 μs shots of emission are consistent with the estimated Galactic scattering time (2.7 μs)¹⁴ for FRB 20180916B.

To test whether the single time bin spikes that appear in B4-sb2 (panel l, Figure 1) are physical or consistent with amplitude-modulated noise^{37,38}, we remove the envelope of the burst from the data. To do this we use a Blackman window function, with a smoothing window of 19 bins, to create a model of the envelope of the burst (shown in panel c of Figure 2). This model is then divided out of the data, leaving the residuals shown in panel d of Figure 2, with off-burst noise also shown for comparison. We find no statistical outliers in this burst, implying that the narrow features are consistent with amplitude-modulated noise. Additionally, we compute the correlation coefficients of the spectra of individual time bins, as a function of time lag between the two spectra that are being correlated in each case (Figure 2, panel f). Cordes et al.³⁹ determine that if the scattering time is larger than the separation of bursts, and each burst is perfectly correlated, the predicted correlation coefficient is 1/3. We measure a S/N weighted correlation coefficient < 0.2 . Due to the large scatter, we cannot distinguish between a constant or slightly decreasing correlation coefficient as a function of lag. Based on the data in hand, we can rule out that burst B4 is comprised of a few well-separated bright (sub) μs shots of emission, but it is possible that the burst envelope is made up of many closely spaced (sub) μs shots of comparable amplitude. This has been predicted in models of magnetospheric burst emission, in order to explain the observed flux densities⁴⁰.

By eye, B4-sb1 (panel k, Figure 1) appears to fluctuate quasi-periodically. To test this hypothesis, we computed the autocorrelation function (ACF; defined by Equation 1 in Marcote et al.¹⁴), and the power spectrum (Figure 3). The power spectrum (in log space) was fit with a power law of the form

$$f(\nu) = A\nu^{-\alpha} + C, \quad (2)$$

where A is the amplitude, α is the power law slope, and C is a white noise component, using the Bayesian analogue of a maximum likelihood estimation using the Stingray modelling interface⁴¹. There are many astrophysical phenomena whose lightcurve is observed to have a power law component in the Fourier domain, often referred to as ‘red noise’ (e.g. gamma-ray bursts;⁴² active galactic nuclei;⁴³ magnetars;⁴⁴). We perform a goodness-of-fit test by simulating 1000 fake power spectra from the best fit, and performing the same Bayesian maximum likelihood fit. The measured p-value is then the fraction of the simulations with a maximum likelihood lower than the likelihood of our fit. The results of this analysis are shown in Table 1. There are apparent oscillations in the ACF, consistent with the fluctuations seen in the profile. The power spectrum shows a power law slope, consistent with red noise. To test the statistical significance of any features in the power spectrum on top of the red noise slope, we use two metrics (for a detailed explanation, see Huppenkothen et al.⁴⁴). First, to search for any significant narrow features in the power spectrum, we compute the residuals as a function of frequency,

ν ,

$$R(\nu) = \frac{2P(\nu)}{M(\nu)}, \quad (3)$$

where $P(\nu)$ is the power spectrum, and $M(\nu)$ is the best fit noise component. Using the Markov chain Monte Carlo (MCMC) package *emcee*⁴⁵ to generate 100 simulated residuals, we generate the distribution of $\max(R_{\text{sim}}(\nu))$, and determine the probability that the observed peak value, $\max(R(\nu))$, is consistent with noise. We find no statistically significant outliers using this statistic. The second method we use is more sensitive to lower amplitude, wider features in the power spectrum, which are often referred to as quasi-periodic oscillations (QPOs) and are observed in a number of astrophysical phenomena (e.g. accreting low-mass X-ray binaries; e.g.⁴⁶ black hole binaries; e.g.⁴⁷ magnetar X-ray flares; e.g.⁴⁸). This second method is a model comparison method. In addition to the red noise fit described above, we fit a function with a Lorentzian describing the QPO summed with a red noise power law (as defined above). We calculate the likelihood ratio, and calibrate this likelihood ratio using MCMC simulations of the simpler model (in our case, the power law model; see Protassov et al.⁴⁹ for details). This analysis returns a posterior predictive p-value of 0.188, i.e. we cannot rule out the simpler model of a red noise power law slope. For all of the Bayesian fits described we give conservative prior distributions: flat distribution for the power law slope α , flat distribution for the amplitude A , normal distribution for the white noise component C , and a flat distribution for the Lorentzian parameters. Since we see fluctuations of $\sim 60 \mu\text{s}$ in the ACF of B4-sb1, we use this as the initial guess for the centroid frequency of the Lorentzian.

The bright envelope of burst B4-sb2 dominates in both the ACF and power spectrum, and so any features associated with quasi-periodic oscillation are difficult to detect. One way to bypass this issue would be to remove the envelope (divide out a smooth model of the burst envelope), but this can introduce features in the power spectrum which are not physical⁴⁴. We therefore only repeat the analysis on burst B3, which does not have a prominent envelope that would dominate the results. Again, we find no statistical outliers. The results are shown in Figure 3 and Table 1. In summary, we find that bursts B4-sb1 and B3 are consistent with red noise, with a power law index of $\alpha = 1.66 \pm 0.02$ and $\alpha = 1.31 \pm 0.02$, respectively. Typically, magnetar X-ray bursts show steeper red noise spectra ($\alpha \approx 2\text{--}5$;⁴⁴).

3 Polarimetric data, analysis and results

For the polarimetric study of the four bursts from FRB 20180916B, we generated full-polarisation, coherently de-dispersed, filterbank data with time and frequency resolutions of 16 μs and 62.5 kHz, respectively, using SFXC (similar to the 1 μs data described in the previous section). Using PSRCHIVE³⁶, we created archive files from the filterbanks at the native time and frequency resolution, and masked channels contaminated by RFI and subband-edge artefacts.

We did not perform a polarisation calibrator scan to use for polarimetric calibration. Instead, we use the test pulsar

observation of PSR B2111+46 to determine the calibration solutions to apply to our target data. A similar polarimetric calibration technique was used for radio bursts detected from SGR 1935+2154 using voltage data with the VLBI backend of the Westerbork single-dish telescope RT1⁵⁰.

We assume that any leakage between the two polarisation hands only affects Stokes V (defined as $V = LL - RR$ using the PSR/IEEE convention⁵¹). We also assume that the delay between the two polarisation hands only significantly affects Stokes Q and U. The calibration we apply ignores second-order effects. We performed a brute force search for the RM that maximises the linear polarisation fraction using the PSRCHIVE tool `rmfit`. The delay between the polarisation hands approximately manifests as an offset from the true RM of the source, assuming the delay is frequency-independent. For PSR B2111+46, we measure an RM of -657 rad m^{-2} , which is ~ 438 units from the true RM of PSR B2111+46 ($-218.7 \text{ rad m}^{-2}$)⁵². This approximately translates to a delay of $\sim 5.5 \text{ ns}$. We use the `rmfit`-RM to Faraday correct the pulsar data, and we reproduce the polarimetric properties and PPA of PSR B2111+46 within 6% of published properties⁵³. Figure 5 illustrates the calibration we applied. We note that, unfortunately, we had < 1 minute on PSR B2111+46 which has a period of $\sim 1 \text{ s}$ ⁵⁴, so it is likely that our observed average profile did not completely stabilise to the published average profile.

We assume there are no significant changes to the calibration required between the test pulsar scan and the detected FRB 20180916B bursts (< 1 hr between the PSR B2111+46 scan and burst B1). Bursts B1 and B4 have a sufficient S/N to determine an RM using `rmfit`. B1 and B4 are separated in time by > 4 hr and we note their measured `rmfit`-RMs differ by approximately 8 units ($\sim 1\text{--}2\%$ of the measured value), which is well within the errors from `rmfit`. Thus we conclude that the bursts have consistent RMs. The measured `rmfit`-RM for B4 is -536 rad m^{-2} , which when combined with the offset due to a delay between the polarisation hands ($+438$ units, measured using the PSR B2111+46 data) gives a true RM of -98 rad m^{-2} .

To better determine the burst RM and associated errors, we perform a joint least squares fit of Stokes Q and U spectra (as a function of frequency, ν), using the following equations:

$$Q/I = L \cos(2(c^2 \text{RM}/\nu^2 + \nu\pi D + \phi)), \quad (4)$$

$$U/I = L \sin(2(c^2 \text{RM}/\nu^2 + \nu\pi D + \phi)), \quad (5)$$

where c is the speed of light, and the free parameters L , the linear polarisation fraction, D , the delay between polarisation hands, and $\phi = \phi_\infty + \phi_{\text{inst}}$, where ϕ_∞ is the absolute angle of the polarisation on the sky (referenced to infinite frequency), and ϕ_{inst} is the phase difference between the polarisation hands. We perform the joint fit on Q/I and U/I spectra for PSR B2111+46 and for burst B4, where the delay, D , is assumed to be the same for both the pulsar and target scans. We fix the known RM of PSR B2111+46⁵², $-218.7 \text{ rad m}^{-2}$. We measure $D = 5.4 \pm 0.2 \text{ ns}$, consistent with our prediction from the offset in RM from the true RM of PSR B2111+46 using `rmfit`. Additionally, we measure the RM of burst B4 to be $-104 \pm 20 \text{ rad m}^{-2}$, where the large fractional error arises due to covariances between the fit parameters (RM, D and ϕ) that could not be removed as we

did not record independent information from a polarisation calibrator source. We find the RM to be consistent with the previously measured RM values for FRB 20180916B^{4,32}.

In Figure 4, we show the Faraday-derotated profiles for the four FRB 20180916B bursts. We use the `rmfit`-determined RM for B4 to correct all four bursts, since B4 has the highest S/N, and we assume the RM does not change between bursts separated by ~ 4 hours. We plot the unbiased linear polarisation, L_{unbias} , profile in red, following Everett & Weisberg⁵⁵, where

$$L_{\text{unbias}} = \begin{cases} \sigma_I \sqrt{\left(\frac{L_{\text{meas}}}{\sigma_I}\right)^2 - 1}, & \text{if } \frac{L_{\text{meas}}}{\sigma_I} \geq 1.57 \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

where $L_{\text{meas}} = \sqrt{Q^2 + U^2}$, and σ_I is the standard deviation in the off-burst Stokes I .

To correct for parallactic angle, we rotate the linear polarisation vector by

$$\theta = 2 \tan^{-1} \left(\frac{\sin(\text{HA}) \cos(\phi)}{(\sin(\phi) \cos(\delta) - \cos(\phi) \sin(\delta) \cos(\text{HA}))} \right), \quad (7)$$

where HA is the hour angle of the burst, ϕ is the latitude of Effelsberg, and δ is the declination of FRB 20180916B. The parallactic angle corrected PPA is shown in the top panel of each sub-figure in Figure 4. We plot the probability distribution of PPA per time bin, following Everett & Weisberg⁵⁵, and mask any bins where the unbiased linear S/N is below 3. We performed a least-squares fit of a horizontal line to the PPA of the four bursts together, weighted by their $1\text{-}\sigma$ errors. We note that for all of the PPA fits, we consider only additive noise in the determination of the variance. The weighted χ^2 -statistic for this global fit is 168.36, with 123 degrees of freedom. We have shifted the absolute value of the PPA by this best-fit value, -89.2° . We note that, due to imperfect calibration, this value is not the absolute PPA and should not be used for comparison with other bursts from other studies of FRB 20180916B. We performed individual least-square fits for each burst. The weighted χ^2 -statistic, degrees of freedom and PPA offset from the global PPA are shown in Table 2. For the above fits, we only included PPAs within the Gaussian-fit $2\text{-}\sigma$ temporal width region (illustrated by the light cyan bars shown in Figure 4) that also satisfied $L_{\text{unbias}}/\sigma_I > 3$. We find that the PPA of the four bursts are consistent with being constant across the burst duration. We do, however, see a hint of PPA variation between burst components (which is most evident in B1 and B3).

In Table 2, we show the linear and circular polarisation fractions, also calculated within the $2\text{-}\sigma$ region of the Gaussian fit. We note that removing the baseline can result in the condition $I^2 \geq Q^2 + U^2 + V^2$ not being satisfied, which, in our case, can lead to apparent linear polarisation fractions $> 100\%$. The errors quoted in Table 2 are $2\text{-}\sigma$ statistical errors. We ignore calibration uncertainties and the effect of removing the baseline in this error determination. We find that all four bursts are highly-linearly polarised ($> 80\%$), and show no evidence for circular polarisation ($< 15\%$). Additionally, the PPA of each burst is consistent with being flat across the burst duration, with the absolute PPA within $\sim 7^\circ$ between bursts. The second spike in the B3 profile

(indicated by an orange bar in Figure 4) appears to have a significantly lower linear polarisation fraction, than the rest of the burst. As we have shown in §2, this component is actually only a few μs wide (Figure 1), therefore this low polarisation fraction can be attributed to the fact that this component is not resolved in the 64 μs time resolution data.

In addition, we show the PPA and polarisation profile of B4-sb2 (purple component in Figure 4) at 1 μs resolution in the lower panel of Figure 4. At this resolution, there is evidence for small ($\sim$ few degrees) variations in the PPA across this bright burst component. To test the significance of these variations, we performed a weighted least-squares fit of a flat PPA to the 1 μs resolution PPAs across the bright burst component of B4. The measured reduced- χ^2 of this fit is 4.2, compared with a reduced- $\chi^2 \approx 1$ for the 16 μs resolution data. We conclude that the variations are significant.

4 Discussion

Implications for progenitor models

Neutron stars are prodigious generators of short-duration radio bursts, including canonical radio pulsar emission⁵⁶, giant pulses like those observed from the Crab pulsar^{57,58}, and radio bursts from magnetars⁵⁹. The Crab pulsar shows a variety of emission features at different radio frequencies⁶⁰, each with their own characteristic spectro-tempo-polarimetric properties⁶¹. Hessels et al.³³ have previously commented on the very similar phenomenology seen when comparing FRB 20121102A with the high-frequency interpulses (HFIPs) produced by the Crab pulsar. Like FRB 20121102A and FRB 20180916B, the Crab pulsar HFIPs typically show high (~ 80 – 90%) linear polarisation, weak (~ 10 – 20%) or undetectable circular polarisation, and non-varying PPA within and between bursts⁶¹. Hankins et al.⁶¹ conclude that since HFIPs are observed to be highly polarised, this implies that the emission region is spatially localised (as opposed to coming from an extended region from the neutron star surface to the light cylinder, which would ultimately lead to depolarisation; e.g.⁶²). Additionally, the flat PPAs between HFIPs suggest that the magnetic field direction is stable during each observational epoch. There have been examples of HFIPs, however, that deviate from this trend, either showing significant circular polarisation, weaker linear polarisation and/or a significant PPA variation across the burst profile⁶¹.

Comparing phenomenology with the Crab pulsar is tempting, but ignores the fact that FRB 20121102A, FRB 20180916B and other repeaters produce radio bursts that are orders of magnitude longer duration and higher luminosity. Indeed, Lyutikov⁶³ argue that the established extragalactic distances of FRBs preclude rotational energy and support magnetic energy as the fundamental power source for the bursts. Many FRB theories have invoked a magnetar as the central engine (see Platts et al.⁶⁴ for a catalogue of FRB theories). The recent discovery of an exceptionally bright (kJy–MJy) millisecond-duration radio burst from the Galactic magnetar SGR 1935+2154 has added compelling evidence for such a scenario^{18,19}. In fact, SGR 1935+2154 has been observed to produce sporadic ra-

dio bursts spanning more than 7 orders-of-magnitude in fluence⁵⁰, though it is unclear whether these all arise from the same physical mechanism.

FRB models that invoke a magnetar as the central engine come in a variety of flavours. First, there is debate about whether the radio burst emission originates within or close to the magnetosphere (e.g.⁶⁵), or whether it is generated in a relativistic shock produced by an explosive energy release from the central engine (e.g.²¹). Secondly, one can consider whether the magnetar is acting in isolation, or whether its activity is stimulated by an external plasma stream (e.g.⁶⁶).

As with pulsars, the polarimetric properties of magnetar radio bursts show diversity^{67,68}. Nonetheless, very high ($> 80\%$) linear polarisation fractions are common⁶⁹, though not ubiquitous^{50,67}.

The high linear polarisation observed for FRB 20180916B is expected for both magnetospheric magnetar models²⁰ and synchrotron maser shock models (e.g.²¹). The magnetospheric model described in Lu et al.²⁰ additionally predicts small variations of the PPA between bursts from a repeating FRB, with the burst-to-burst variability following the rotation period of the magnetar. Relativistic shock models, where the FRB emission originates much farther from the magnetar, naturally predict constant PPA within and between bursts (e.g.²¹). However, small variations can be explained by invoking clumpiness in the medium into which the shock front propagates, or could alternatively come from the maser emission itself (although at this time, it is unclear how large an effect this will have on the PPA).

In this work, we have observed the shortest timescale structure in any FRB, to date. In the four bursts presented here, the range of timescales is from a few μs to a few ms. In the literature, there are bursts detected from FRB 20180916B up to widths of 6 ms (at 300–800 MHz)^{4,32}, although there could be a frequency dependence on burst width. The observed shortest timescales of a few μs , and range of timescales observed in FRB 20180916B bursts also have implications for magnetar progenitor FRB models. Beniamini & Kumar⁷⁰ consider the scenario where the FRB emission originates at some distance from a magnetar as a relativistic outflow moving towards the observer. It is argued that the fluctuations on the light-curve strongly constrain where the emission originates (i.e. within the magnetosphere or well outside the magnetosphere). The ratio of fluctuations to total burst duration, in our case, is $\sim 5 \mu\text{s} / 2 \text{ ms} = 0.0025 \ll 1$, which is most naturally explained invoking emission originating within the magnetosphere. The short timescale structure observed in FRB 20180916B implies that the emission region is on the order of 1 km. In the case of FRB emission originating from a relativistic shock at a large distance from the magnetar, this would imply a very small area of the total shock front dominating. This, and the temporal fluctuations can be explained by invoking clumpiness in the medium where the shock front propagates, or potentially propagation effects could be playing a role (e.g. refraction).

The consistent PPA between bursts from FRB 20180916B has direct implications regarding the precessing neutron star model invoked to explain the 16.35 day periodicity (e.g.⁷¹). During the precession, the

line of sight inevitably sweeps across much larger angular area on the neutron star/magnetar surface compared to the non-precessing case. Therefore, the model not only expects PPA variation as a function of the rotational period, it also expects PPA variation as a function of precession phase. A small PPA variation between the bursts strongly suggests that the emission angle is greatly tilted from the direction of the magnetic pole in this scenario.

Characteristic observational description of repeating FRBs

Our high-time-resolution, polarimetric measurements of FRB 20180916B demonstrate remarkable phenomenological similarity to FRB 20121102A, the only other repeating FRB with published polarimetric profiles for multiple bursts within a single observing session^{16,29}. Both of these repeating FRBs show $\sim 20\text{--}30\ \mu\text{s}$ sub-bursts (in some high-S/N bursts, at least), $\sim 100\%$ linear polarisation, $\sim 0\%$ circular polarisation, and a constant PPA during the bursts. Moreover, between 16 bursts found in three observations spanning 25 days, Michilli et al.¹⁶ report consistent PPAs throughout. Michilli et al.¹⁶ fit for a variable RM per day, but a global PPA for all epochs. Gajjar et al.²⁹ quote different average PPAs between bursts, but this is potentially because they allow the RM to vary between bursts detected within a $\sim 1\text{-hr}$ range. The covariance between RM and PPA makes it difficult to distinguish small variations in the former compared to the latter. Here we find that the PPA of FRB 20180916B is also remarkably similar *between* bursts, as shown in Figure 4 and Table 2.

Comparing our 1.7-GHz measurements with the available 300–400 MHz GBT³² and 400–800 MHz CHIME/FRB⁴ bursts, we find that the polarimetric properties are also persistent over a wide range of radio frequencies. However, the lack of absolute PPA calibration prevents us from investigating whether the average PPA is both persistent in time and between radio frequencies. In the case of FRB 20121102A, it appears that the linear polarisation fraction decreases towards lower frequencies (Plavin et al., in prep.). It is, as yet, unclear whether that is due to an intrinsic change in the emission physics, or whether it reflects a propagation effect. The RM of FRB 20121102A is highly variable^{16,29,30}, and 2–3 orders of magnitude larger than FRB 20180916B. The association of FRB 20121102A with a persistent, compact radio source^{10,12} – whereas none is detected coincident with FRB 20180916B¹⁴ – further demonstrates that their local environments are different, despite both being coincident with a star-forming region^{11,14,72}.

Regardless of differences in host galaxy type and the local environment, however, the remarkable similarity of burst properties demonstrates that FRB 20121102A and FRB 20180916B have the same physical origin. This is further emphasised by the detection of periodicity in the burst activity rate of FRB 20180916B $P_{\text{activity}} \sim 16\text{ day}$,⁷³ and the potential detection of a similar effect from FRB 20121102A $P_{\text{activity}} \sim 157\text{ day}$,^{74,75}.

To date, the only other repeating FRB that has polarisation information from more than one burst, and is localised to a host galaxy, is FRB 20190711A^{24,31}. FRB 20190711A

clearly shows the downward-drifting ‘sad trombone’ effect characteristic of repeating FRBs^{33,34}. Also, the polarimetric properties of FRB 20190711A show a striking observational similarity; it is also highly linearly polarised, $\sim 0\%$ circularly polarised and has a constant PPA across the burst profiles. FRB 20190711A has been localised to a star-forming galaxy^{76,77}, different from the hosts of FRB 20121102A (found in a faint starburst galaxy¹⁰) and FRB 20180916B (localised to a massive quiescent galaxy¹⁴).

The so-far non-repeating FRB 20181112A shows 4 sub-bursts spanning a total burst duration of 1.5 ms, with different apparent RMs and DMs between sub-bursts¹⁷. Day et al.²⁴ also found similar effects in their sample of five FRBs. The apparent RM variations of $\sim 10\text{--}20\text{ rad m}^{-2}$ seen in the ASKAP FRB sample are too subtle to probe for FRB 20180916B given the data we present here and the uncertainty on the delay calibration. We note, however, that (apparent) RM variations at this level are likely excluded based on previously published FRB 20180916B polarimetric results taken at 400 – 800 MHz using CHIME/FRB⁴ because they would lead to a lower polarisation fraction than observed.

Nonetheless, at the high-time-resolution afforded by these data, we detect subtle PPA variations of a few degrees between sub-bursts lasting $\lesssim 100\ \mu\text{s}$ each. This is most visible for burst B1 (Figure 4). For the bright, $\sim 60\ \mu\text{s}$ dominant component of B4 (B4-sb2), where we have maximum S/N per unit time, there is the suggestion of PPA variations of a few degrees, when studying this component at $1\ \mu\text{s}$ time resolution (Figure 4). This could be interpreted as potential small PPA swings, or that this burst component is actually composed of many sub- μs components with PPAs that vary on the level of a few degrees, similar to what we see between the $\sim 100\ \mu\text{s}$ burst components.

FRB 20180916B shows some of the shortest-timescale temporal features seen in any FRB to date. For comparison, FRB 20121102A, FRB 20170827A and FRB 20181112A have shown $\sim 30\ \mu\text{s}$ substructures^{15–17}. In the case of FRB 20170827, the burst shows a single component of width $\sim 30\ \mu\text{s}$ ¹⁵, and similarly, FRB 20121102A produced a single burst of width $\sim 30\ \mu\text{s}$ ¹⁶. FRB 20181112A, also shows a single narrow component, but the results are limited by scattering at the $20\ \mu\text{s}$ level¹⁷. In this work, we have demonstrated that not only does FRB 20180916B also exhibit short duration components similar to what has been seen in other FRBs (e.g. the $\sim 30\ \mu\text{s}$ spike in the inset on Figure 4), but in fact, we observe temporal scales spanning three orders of magnitude, the shortest reaching only a few μs .

Marcote et al.¹⁴ estimated a Galactic scattering time of $2.7\ \mu\text{s}$ at 1.7 GHz from the measurement of the scintillation bandwidth. Independently, Chawla et al.³² place a constraint on the scattering timescale of FRB 20180916B of $\tau < 1.7\text{ ms}$ at 350 MHz, which, assuming a frequency scaling of $\tau \propto \nu^{-4}$, gives a scattering time at 1.7 GHz of $< 3\ \mu\text{s}$, consistent with Marcote et al.¹⁴. The shortest timescale structure observed in this work is consistent with this scattering prediction. Our results rule out that burst B4 is composed of a few extremely bright sub- μs shots of emission well-spaced in time, similar to what is observed in Crab gi-

ant pulses⁵⁷. If the $\sim 20 \mu\text{s}$ morphology that we observe in the profile of B4 are made up of sub- μs shots of emission, they must be closely-packed in time and of approximately equal amplitude.

There is a consistent characteristic picture emerging for repeating FRBs. Specifically, repeaters exhibit the downward drifting, so-called ‘sad-trombone effect’, in frequency^{4,33}, and show narrowband burst envelopes (e.g.⁷). On average, repeating FRBs exhibit longer duration burst profiles⁴. And additionally, the repeaters FRB 20121102A, FRB 20180916B and FRB 20190711A show remarkably consistent and characteristic polarimetric properties (highly linearly polarised, no evidence of circular polarisation, and constant PPA during and between bursts). In contrast, the global landscape of FRB polarimetric properties is diverse^{23,24}. As with pulsars, FRBs have shown a wide range of linear and circular polarisation fractions and PPA variations. Repeating FRBs appear to live in a very diverse set of host galaxies and local environments^{10,14,77}, implying that these characteristic properties are exclusive to the emission mechanism, as opposed to effects from the local medium. In this work, we have supported this characteristic picture with our polarisation measurements of FRB 20180916B at 1.7 GHz. We also suggest that the dynamic range of temporal structure of $2 \text{ ms}/5 \mu\text{s} \sim 400$ could be another characteristic to add to this overall description of repeating FRBs.

The results presented here highlight the importance of high-time-resolution polarimetric studies of FRBs. With lower time resolution data, narrow temporal components and subtle variations in the PPA are averaged out. It is possible that previous flat PPA measurements from FRB 20121102A and FRB 20180916B are a result of this. We encourage future observations of FRBs with $\sim \mu\text{s}$ time resolution and full polarisation information, and we also encourage searches for QPOs in individual high S/N FRBs, like the analysis conducted in this work. Studying FRBs in this detail (also observing the spectral and long-term temporal evolution of repeaters) are crucial in understanding the emission physics.

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Additional information

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Competing interests

The authors declare no competing interests.

Figure 1: Burst profiles at 16 μ s and 1 μ s time resolution for four 1.7 GHz bursts from FRB 20180916B. The burst name (B1–B4) and time resolution used for plotting is shown in the top right of each panel. Bursts B3 and B4 show complex temporal structure. Panels i and j are zoomed-in 1 μ s resolution data around the B3 burst components highlighted by the orange and purple bars in panel g, respectively. Similarly for burst B4, panels k and l are zoomed-in 1 μ s resolution data around the B4 burst components highlighted by the orange and purple bars in panel h, respectively. Overplotted on panels j, k and l is a smoothed profile using a Blackman window function with a window length of 19 bins.

Figure 2: Stokes I burst profile of the bright component of burst B4 (B4-sb2) sampled at $1 \mu\text{s}$ resolution (panel a). The inset on panel a shows the profile of B4 at $16 \mu\text{s}$ resolution, with the shaded region indicating the extent of the profile shown in the panel. The dynamic spectrum is shown in panel b. Panel c shows the profile again, overplotted with a smoothed profile using a Blackman window function with a window length of 19 bins. The burst profile was “de-enveloped” by dividing out the smoothed profile, and the residuals are shown in black in panel d. Also shown in panel d is the de-enveloped off-burst time series in green, for comparison. In panel e, we show the histogram of the on-burst and off-burst residuals. Panel f shows the correlation coefficient of the spectra of bins with $\text{S/N} > 10$ in the main peak of B4, as a function of time between the spectra in μs . The colour bar represents the geometric mean S/N of the two time bins that have been correlated, with the darker purple representing a higher S/N . Overplotted in black is the weighted mean and standard deviation per time lag.

Table 1: Results of power spectrum fitting

Burst	Power law slope (α)	Goodness of fit p-value ^a	Posterior predictive p-value ^b	Residual outlier p-value ^c
B4-sb2	1.66 ± 0.02	0.424	0.188	0.40
B3	1.31 ± 0.02	0.387	0.784	0.87

^aGoodness of fit of the power law red noise model described by Equation 2.

^bModel comparison of power law red noise model, versus a power law plus lorentzian (to describe a quasi-periodic oscillation). See text for details.

^cp-value of the highest outlier in the residuals of the power spectrum divided by the best fit power law slope.

Figure 3: The time profile of bursts B4-sb1 (top frame) and B3 (bottom frame), are shown in the top left of each frame. The autocorrelation function (ACF) of the time profiles shown (bottom left of each frame). The power spectrum of the time profiles shown (top right of each frame), and the orange is the power spectrum downsampled in frequency by a factor of 3. Overplotted in pink on the power spectrum is the best fit power law plus white noise component. Bottom right is the residuals ($2 \times \text{power spectrum} / \text{best fit model}$).

Figure 4: Polarimetric profiles (lower panels of each sub-figure) and PPAs (top panels of each sub-figure) for the four bursts from FRB 20180916B discovered during an EVN campaign on 2019 June 19¹⁴. In the bottom panels, the total intensity (Stokes I) profile is shown in black, the unbiased linear polarisation (Equation 6) is shown in red, and circular polarisation (Stokes V) is shown in blue. For B1, B2 and B3, we plot 8 ms around the burst, and for B4 we plot 4 ms. The time is referenced to the mean of the Gaussian fit to the burst envelope discussed in Marcote et al.¹⁴. The inset in the lower panel of B4 shows a zoom-in on the profile at the leading edge, highlighting a narrow, $\sim 30 \mu\text{s}$, spike, also highlighted by the green arrow. The top left of each lower panel shows the burst name, B_n , used to define the bursts in this work (ordered according to their arrival time), and the time resolution used for plotting. Also shown in the lower panels are the Gaussian full-width at half-maximum (FWHM) of each burst illustrated by the dark cyan bar. The light cyan bar represents the $2\text{-}\sigma$ region. Bursts B3 and B4 show multiple sub-bursts indicated by the orange, purple and green bars (the FWHM is shown in the dark colour, and the $2\text{-}\sigma$ region shown in the lighter colour). For burst B4, we also show dotted lines indicating the extent of the three sub-bursts (B4-sb1 (orange), B4-sb2 (purple) and B4-sb3 (green)). The top panel shows the PPA, defined as $\text{PPA} = 0.5 \tan^{-1} (U/Q)$. The greyscale represents the probability distribution of the PPA following Everett & Weisberg⁵⁵, the darker shading representing higher polarised S/N. The PPA has been shifted by the best-fit flat PPA of the four bursts, weighted by the unbiased linear signal-to-noise, meaning the weighted PPA of the four bursts is zero and is illustrated by the green line. The bottom sub-figure shows B4-sb2 (shaded region of the $16 \mu\text{s}$ resolution B4 profile) of B4 plotted with $1 \mu\text{s}$ resolution (bottom panel), and the PPA across the burst (top panel). On the right of the bottom panel, the off burst standard deviation is shown.

Table 2: Burst polarisation properties and polarisation position angle fit results.

Burst	MJD ^a	Fluence [Jy ms] ^{a,b}	L_{unbiased}/I [%] ^{c,d}	V/I [%] ^{c,d}	PPA offset [deg] ^c	χ^2	Degrees of freedom
B1	58653.0961366466	0.72	107 ± 14	-1 ± 10	-3.34	42.99	24
B2	58653.1112573504	0.20	85 ± 20	-4 ± 20	-5.99	0.87	2
B3	58653.1465969404	0.62	97 ± 14	-15 ± 14	0.29	23.80	13
B4	58653.2785078914	2.53	103 ± 4	5 ± 4	0	92.52	81
B4-sb2 (1 μ s)	-	-	-	-	-0.29	494.14	119

^aFor details on the determination of these values see Marcote et al. ¹⁴.

^bA conservative fractional error of 30% is taken for the derived fluences.

^cThe fractional polarisations and PPA values are measured over the Gaussian-fit 2σ region of the burst profile,

^dThe errors quoted are statistical 2σ errors assuming the errors in the Stokes parameters are independent of each other, and the error in each time bin is independent of one another.

The uncertainties do not contain the calibration uncertainty nor do they encapsulate the effect of removing the baseline.

Figure 5: The average polarisation profiles (bottom panels) and polarisation position angle (top panels) of PSR B2111+46. Black represents the Stokes I profile, red is the unbiased linear polarisation profile (defined in Everett & Weisberg ⁵⁵, and rewritten here in Equation 6), and blue is the circular polarisation (Stokes V) profile. The left panel shows the polarisation profile and position angle after Faraday-correcting to the true rotation measure of PSR B2111+46 ($-218.7 \text{ rad m}^{-2}$; Force et al. ⁵²), i.e. we are ignoring the delay between polarisation hands which has not been corrected for. The right panel is Faraday-corrected using the rotation measure determined using the PSRCHIVE tool `rmfit`, which, in essence, accounts for the delay. For comparison, we plot the profile and position angle from the literature using more transparent colours ⁵³. This illustrates the calibration we applied to the bursts from FRB 20180916B.

Figures

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