Scattering variability detected from the circumsource medium of FRB 20190520B

Stella Koch Ocker,1* James M. Cordes,1 Shami Chatterjee,1 Di Li,2,3 Chen-Hui Niu,2 James W. McKee,4,5 Casey J. Law,6,7 and Reshma Anna-Thomas8

1Department of Astronomy and Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY 14850, USA
2National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China
3Research Center for Intelligent Computing Platforms, Zhejiang Laboratory, Hangzhou 311100, China
4E.A. Milne Centre for Astrophysics, University of Hull, Cottingham Road, Kingston-upon-Hull, HU6 7RX, UK
5Centre of Excellence for Data Science, Artificial Intelligence and Modelling (DAIM), University of Hull, Cottingham Road, Kingston-upon-Hull, HU6 7RX, UK
6Cahill Center for Astronomy and Astrophysics, MC 249-17 California Institute of Technology, Pasadena, CA 91125, USA
7Owens Valley Radio Observatory, California Institute of Technology, 100 Leighton Lane, Big Pine, CA, 93513, USA
8Department of Physics and Astronomy and the Center for Gravitational Waves and Cosmology, West Virginia University, Morgantown, WV 26506, USA

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Abstract

Fast radio bursts (FRBs) are millisecond-timescale radio transients, the origins of which are predominantly extragalactic and likely involve highly magnetized compact objects. FRBs undergo multipath propagation, or scattering, from electron density fluctuations on sub-parsec scales in ionized gas along the line-of-sight. Scattering observations have located plasma structures within FRB host galaxies, probed Galactic and extragalactic turbulence, and constrained FRB redshifts. Scattering also inhibits FRB detection and biases the observed FRB population. We report the detection of scattering times from the repeating FRB 20190520B that vary by up to a factor of two or more on minutes to days-long timescales. In one notable case, the scattering time varied from 7.9 ± 0.4 ms to less than 3.1 ms (95% confidence) over 2.9 minutes at 1.45 GHz. The scattering times appear to be uncorrelated between bursts or with dispersion and rotation measure variations. Scattering variations are attributable to dynamic, inhomogeneous plasma in the circumsource medium, and analogous variations have been observed from the Crab pulsar. Under such circumstances, the frequency dependence of scattering can deviate from the typical power-law used to measure scattering. Similar variations may therefore be detectable from other FRBs, even those with inconspicuous scattering, providing a unique probe of small-scale processes within FRB environments.

Key words: transients: fast radio bursts – stars:neutron – stars: magnetars – scattering – plasmas

1 Introduction

FRB 20190520B is only the second fast radio burst (FRB) localized to a dwarf galaxy and associated with a compact persistent radio source (PRS), presumably from a synchrotron nebula surrounding the source (Niu et al. 2022). Its total line-of-sight (LOS) integrated electron density \( n_e \), or dispersion measure \( DM = \int_0^{z_h} n_e(l) dl \), is dominated by the host galaxy at redshift \( z_h = 0.241 \), which contributes \( DM_h = 903 \pm 72 \) pc cm\(^{-3} \) (observer frame), at least three times the DM typically inferred for the host galaxies of non-localized FRBs (Niu et al. 2022; Luo et al. 2018; Shin et al. 2022). Like some other repeating FRBs, FRB 20190520B shows extreme variations in rotation measure (RM), which are attributed to path-integrated magnetic field changes within its local environment (Feng et al. 2022; Anna-Thomas et al. 2022; Dai et al. 2022).

FRB 20190520B also shows evidence of significant scattering, observed as both pulse broadening with a corresponding temporal delay \( \tau \) (aka the scattering time), and scintillation with a corresponding frequency bandwidth \( \Delta \nu_d \). In Ocker et al. (2022), hereafter O22, we measured a mean scattering time \( \bar{\tau}(1.41 \text{ GHz}) = 10.9 \pm 1.5 \text{ ms} \) at 1.45 GHz and a mean scintillation bandwidth \( \Delta \nu_d(1.41 \text{ GHz}) = 0.21 \pm 0.01 \text{ MHz} \) at 1.45 GHz for this source. Attributing \( \tau \) to the host galaxy and \( \Delta \nu_d \) to the Milky Way constrained the mean scattering from the host galaxy to within 100 pc of the source.

In this work we examine individual bursts from FRB 20190520B to characterize scattering variations near the FRB source. Unlike Galactic pulsar scattering, which even for the Crab pulsar varies slowly (longer than days to weeks; McKee et al. 2018), we find that the scattering time can vary significantly between bursts, indicating the presence of plasma inhomogeneities likely on sub-astronomical (au) scales within the circumsource medium (CSM). Section 2 describes the methods used to analyze burst spectra and constrain scattering. Results are presented in Section 3 and compared to other observations of the source in Section 4. Section 5 explores a possible model for the plasma inhomogeneities that give rise to the scattering variations. Implications for the CSM and other FRB sources are discussed further in Section 6.

* E-mail: sko36@cornell.edu
2 METHODS

FRB 20190520B was initially detected in archival data from the Com-mensal Radio Astronomy FAST Survey (CRAFTS; Li et al. 2018; Nan et al. 2011). The burst sample considered in this paper is drawn from tracking observations of the FRB conducted at FAST between April and September 2020, which yielded 75 burst detections across 12 observing epochs in the 1.05 – 1.45 GHz frequency band. These observations were discussed in Niu et al. (2022), and correspond to bursts P5 - P79 in the supplementary information of that paper (for reference, bursts A-D in Figures 1-2 correspond to bursts P28, P34, P66, and P67). The same set of bursts was discussed in O22.

Bursts from FRB 20190520B show a range of morphologies, from burst intensities that are symmetric in time, to spectral islands that drift downward in frequency-time space (the “sad-trombone”), and frequency-dependent temporal widths and intensity modulations that are attributable to scattering (Niu et al. 2022; Ocker et al. 2022). We have taken a number of steps throughout the analysis to mitigate con-fusion of intrinsic structure with scattering asymmetries, including the exclusion of bursts with multiple identifiable components and frequency-time drift from the analysis; the assessment of scattering models in multiple frequency subbands; and the statistical evaluation of burst asymmetries used in the skewness method described below.

2.1 Initial Data Processing

The data were initially recorded in filterbank format with a frequency resolution of 0.122 MHz and a sampling time of 49.5 µs. The data were subsequently smoothed to a temporal resolution of 1.57 ms using a 1D boxcar filter, except for burst D, for which a temporal resolution of 0.59 ms was used to obtain adequate sampling across the burst due to its exceptionally narrow temporal width.

Two de-dispersion methods were explored, one that maximizes burst substructure (Hessels et al. 2019) and one that maximizes the burst signal-to-noise ratio (S/N), defined as burst peak intensity di-vided by the root-mean-square (rms) of the off-burst noise (Cordes & McLaughlin 2003). While structure-optimization is generally fa-vored for bursts that have multiple components and non-dispersive frequency-time drift, the scattering times of such bursts are highly ambiguous even after de-dispersion. We therefore removed bursts identified by eye to have non-dispersive frequency-time drift and/or multiple identifiable components (peak S/N ≥ 5 when averaged across the entire 400 MHz band) and did not consider these bursts in subsequent analysis. For the remaining single-component bursts, we compared the structure-optimized DMs determined in Niu et al. (2022) and S/N-maximized DMs, which were determined by calculat-ing S/N for a range of trial DMs at 0.1 pc cm⁻³ resolution. The peak and width of the resulting ambiguity function were used to determine the best-fit DM and error. There was minimal difference between the structure-optimized and S/N-maximized DMs for most of the single-component bursts in the sample. However, in some cases structure optimization misestimated the DMs of single-component bursts by failing to align the leading edge of intensity across all frequencies, which can result in an overestimated scattering time.1 We therefore use the S/N-maximized DMs in subsequent analysis. All dynamic spectra were individually examined to affirm that the leading edge of intensity was aligned across the burst bandwidth, before proceeding with the scattering analysis.

In most cases, burst intensity is concentrated above 1.3 GHz. We define the burst bandwidth using the minimum and maximum frequen-cies where the time-averaged burst spectrum has a S/N > 2, for a fixed time window of 300 ms around each burst. The central frequency is taken to be the mid-frequency of the burst bandwidth (without any weighting by intensity). The average central frequency of the burst sample is 1.35 GHz. Data from 1.16-1.29 GHz were masked for most bursts due to radio frequency interference (RFI).

2.2 Empirical Burst Widths

We measure the total, empirical width of each burst using the ACF of the burst intensity averaged over the burst’s entire spec-tral bandwidth, ⟨I(t)I(t + δt)⟩. The ACF error at a lag k is

\[ \chi^2 = \frac{1}{n} \sum_{m=1}^{n} r_m^2, \]

where \( n \) is the length of the time series and \( r_m \) is the autocorrelation at lag \( m \) (Priestley 1981). The burst full-width-at-half-maximum (FWHM) is estimated using the half-width-at-half-maximum (HWHM) of the ACF, \( \text{FWHM} = \sqrt{2}\times\text{HWHM}_{\text{ACF}} \) (calculated after removal of the noise spike at zero lag). For a Gaussian burst, this is equivalent to the FWHM that would be derived directly from the pulse shape. In general, FWHM ≈ \( \sqrt{W^2 + W^2_{\text{PBF}}} \) where \( W_i \) is the intrinsic burst width and \( W_{\text{PBF}} \) is the width of the pulse broadening function (PBF).

2.3 Burst Scattering Times

A canonical, robust scattering measurement generally requires that the burst intensity be asymmetric in time, with an extended scattering tail that increases at lower observing frequencies. Accurate identifi-cation of scattering thus requires an assessment not only of the pulse profile in time, but also the evolution of that profile over frequency, which in turn requires precise de-dispersion. For fitting purposes, the burst profile (intensity vs. time) is assumed to consist of a Gaussian pulse convolved with a one-sided exponential PBF, with a \( 1/e \) delay \( \tau \) that scales with observing frequency \( \nu \) as \( \tau \propto \nu^{-3} \). The Gaussian pulse is assumed constant in frequency \( \nu \), while the scattering time \( \tau \), the \( 1/e \) time of the PBF, evolves as \( \tau \propto \nu^{-2} \). Each burst was divided into multiple frequency subbands before averaging over frequency to obtain the temporal burst profile as a function of frequency. The scattering time and Gaussian width were then fit by minimizing the \( \chi^2 \) statistic, and the burst amplitude was left as a free parameter that varied between subbands. While PBFs discerned from pulsar observ-ations can be non-exponential and intrinsic widths can vary with frequency, our simple approach is sufficient for the data in hand.

Scattering times are only reported for bursts that satisfy two main criteria: 1) A combination of sufficient S/N and burst bandwidth – in practice, a S/N ≥ 5 in at least 2 frequency subbands, where a given subband typically needed to be > 20 MHz wide to give the required S/N; and 2) there is a global minimum in \( \chi^2 \), a reduced \( \chi^2 \approx 1 \), and \( \tau \) has a fractional error < 30%. We refer to bursts that fit these criteria as Set 1. Bursts that do not meet these criteria are called Set 2. Set 2 contains both low S/N bursts that do not meet criterion (1), and high S/N bursts that do not meet criterion (2). Scattering may still be relevant to Set 2 bursts because larger scattering can reduce burst S/N, to the point where criterion (1) is no longer met, and because inhomogeneities in the CSM may cause non-exponential PBFs (see Section 6 for further discussion). The methods used to assess these effects are described in the following two sections.

1 Preliminary analysis suggests that structure optimization may appear to misestimate DMs when the intensity varies enough within a burst that brighter components of the burst get overweighted with respect to fainter components. Multi-path propagation may also play a role here, as different paths may have slightly different DMs.
2.4 The Skewness Test

To constrain the presence of scattering for bursts in Set 2, we develop a two-part metric based on the skewness function (Stonebring & Cordes 1981). The skewness function quantifies the degree and direction of asymmetry in a burst of intensity \( I(t) \), and is given by

\[
\kappa(\delta t) = \frac{\langle I^3(t)\rangle - \langle I(t)\rangle \langle I^2(t + \delta t)\rangle}{\langle I(t)\rangle^3},
\]

where brackets denote time averages and \( \delta t \) is a given time lag. Typically the skewness function is normalized using the third moment \( \langle I(t)\rangle^3 \), but this normalization yields a strong S/N dependence that renders large errors for many bursts in our sample. We mitigate this effect by normalizing with the mean \( \langle I(t)\rangle^3 \). For an asymmetric pulse, the skewness function is antisymmetric in \( \delta t \), and maximizes at an amplitude \( \kappa_{\text{max}} \) and a lag \( \delta t_{\text{max}} \). When calculating \( \kappa_{\text{max}} \) and \( \delta t_{\text{max}} \) we only consider lags less than twice the burst width inferred from the ACF.

The two-part skewness test assesses both the sign of \( \delta t_{\text{max}} \) and the amplitude \( \kappa_{\text{max}} \). For an exponential PBF, \( \kappa(\delta t) \) maximizes at \( \delta t_{\text{max}} = r \ln 2 \), and \( \kappa_{\text{max}} \) increases with respect to \( r \). For a Gaussian pulse convolved with an exponential PBF, \( \delta t_{\text{max}} / \ln 2 > r \). Noise can induce both positive and negative temporal asymmetries. For high S/N bursts this effect is negligible and the sign of \( \delta t_{\text{max}} \) for an individual burst provides one piece of evidence for scattering. A sample of noisy, intrinsically symmetric bursts will have equal probability of \( \delta t_{\text{max}} \) being positive or negative, but a sample of noisy, scattered bursts will preferentially have \( \delta t_{\text{max}} > 0 \). One could also argue that intrinsically asymmetric bursts will not preferentially be biased towards positive temporal asymmetries, depending on the emission mechanism (which remains highly uncertain). The distribution of \( \delta t_{\text{max}} \) for a sample of independent bursts is thus also used to assess the presence of scattering.

The second part of the skewness test assesses the amplitude \( \kappa_{\text{max}} \). When the S/N of a given burst is high (the exact S/N threshold depends on the burst width; see Appendix A), the amplitude of the maximum skewness \( \kappa_{\text{max}} \) is compared to the maximum skewness of an exponential PBF with the same total width as the observed burst. The resulting ratio of skewness amplitudes is then compared to the ratio that would be obtained for a Gaussian burst, in order to determine whether the observed skewness is consistent or inconsistent with scattering to a given statistical confidence level. The full procedure for assessing the skewness amplitude \( \kappa_{\text{max}} \) is described in Appendix A.

2.5 Mean Scattering Times from Fourier Domain Stacking

In O22 we demonstrated that stacking bursts’ temporal profiles in the Fourier domain can be used to infer an average scattering time. This method has the advantage of mitigating shifts in burst arrival times both across the frequency band of a single burst and when stacking different bursts. Here we employ an identical routine to compare the average scattering times of bursts in Sets 1 and 2, in order to test

Figure 1. Two scattered bursts detected within 26 minutes. a) Frequency-averaged burst intensity vs. time in units of the signal \( I(t) \) divided by the off-pulse noise \( \sigma_{\text{off}} \) and in four subbands centered on frequencies 1430 MHz (blue), 1390 MHz (orange), 1350 MHz (green), and 1310 MHz (red). Subbands are offset by an arbitrary amount for clarity. Black curves indicate the result of fitting a Gaussian pulse convolved with a one-sided exponential using a least squares fit for a Gaussian width fixed across frequency \( \nu \) and a scattering time \( \tau \). The time resolution is 1.6 ms. b) Dynamic spectrum indicating burst intensity as a function of frequency vs. time. White bands are masked radio frequency interference (RFI). The horizontal black bar indicates the region used to calculate the time-averaged burst spectrum. c) Time-averaged burst spectrum vs. frequency \( \nu \) in units of the signal-to-noise ratio \( I(\nu)/\sigma_{\text{off}} \) (blue curve) and the spectrum smoothed with a 1 MHz-wide boxcar filter (black curve). d) Same as a) - c) for a burst detected below 1200 MHz. The scattering time was fit using the same procedure applied to the three frequency subbands shown in panel d): 1075 MHz (green), 1125 MHz (orange), and 1150 MHz (blue).
Burst D (Figure 2b) stands out as having a much shorter scattering time than bursts in Set 1. It was detected only 2.9 minutes after burst C, with a scattering time that is at least a factor of two smaller. Burst D (Figure 2b) was detected only 2.9 minutes after Burst C, with a scattering time that is at least a factor of two smaller. The ACF of the frequency-averaged burst profile yields an empirical measurement of the burst FWHM, \( W = 2.9 \pm 1.0 \) ms; the contribution of intra-channel dispersion smearing to the burst width is less than 1%. The burst peak S/N = 9.1 is too small to perform a least squares fit for scattering in both frequency and time. Figure 3 shows the results of fitting the 1D burst profile with a Gaussian pulse convolved with an exponential PBF, which yields \( \tau(1.45 \text{ GHz}) = 1.5 \pm 0.4 \) ms and a standard deviation \( \sigma_G = 0.8 \pm 0.2 \) ms with a reduced \( \chi^2 = 1.2 \). For the same Gaussian width, scattering times between 6 and 12 ms at 1.45 GHz (the approximate range of \( \tau \) across the entire burst sample) would yield much larger temporal widths than observed from the burst profile. Fitting a symmetric Gaussian pulse to the burst yields \( \sigma_G = 1.3 \pm 0.1 \) ms with \( \chi^2 = 1.4 \), and hence is not preferred over the exponential model. As the peak S/N is too small to assess the frequency dependence of the burst width, we place a 95\% confidence upper limit on the scattering time of \( \tau \leq 3 \) ms at 1.45 GHz, based on the empirical burst width measured from the ACF. The scattering reference frequency is (conservatively) taken to be the highest frequency at which the burst is detected. The DM of burst D (1197 \pm 3 \text{ pc cm}^{-3}) is marginally different from that of burst C (DM = 1217 \pm 11 \text{ pc cm}^{-3}). The \( \tau \) upper limit for burst D is at least two times smaller than the scattering times measured for bursts A-C and the other bursts with individual scattering measurements, all of which are shown in Figure 4.

### 3 ANALYSIS & RESULTS

#### 3.1 Set 1 Bursts: Measurement of Scattering Variations

Bursts A-C in Figure 1 and Figure 2a show examples of bursts in Set 1, which have best-fit scattering times of \( 6.7 \pm 0.4 \) ms, \( 6.2 \pm 0.7 \) ms, and \( 7.9 \pm 0.4 \) ms at 1.45 GHz for bursts A, B, and C, respectively. Set 1 also contains significant scattering measurements for thirteen other bursts (Table 1), which we compare to bursts in Set 2 below.
measured using a 2D fitting routine that assumes \( \tau \propto \nu^{-4} \), and are referenced to 1.45 GHz by the same assumption. The fitting also assumes the Gaussian FWHM is constant across frequency. DMs shown maximize the S/N. Bursts A-D are indicated with superscripts.

| MJD       | \( \tau \) (ms at 1.45 GHz) | Gaussian FWHM (ms) | DM (pc cm\(^{-3}\)) |
|-----------|-----------------------------|--------------------|---------------------|
| 58991.68687 | 6.5 ± 0.9                  | 5.9 ± 0.7          | 1210 ± 5            |
| 58991.70463 | 6.7 ± 1.4                  | 5.7 ± 2.2          | 1210 ± 4            |
| 58991.71769 | 7.4 ± 0.3                  | 7.5 ± 0.2          | 1219 ± 5            |
| 58991.71788 | 6.1 ± 1.5                  | 5.7 ± 1.5          | 1222 ± 4            |
| 58991.71822 | 8.5 ± 0.2                  | 10.6 ± 0.2         | 1211 ± 7            |
| 59060.48447 | 7.9 ± 0.3                  | 9.7 ± 0.5          | 1187 ± 11           |
| 59060.50785 | 6.9 ± 0.3                  | 4.2 ± 0.5          | 1196 ± 13           |
| 59060.52596 | 7.0 ± 0.3                  | 6.8 ± 0.4          | 1205 ± 10           |
| 59061.52434\(^A\) | 6.7 ± 0.4                | 5.4 ± 0.4          | 1196 ± 9            |
| 59061.54182\(^B\) | 6.2 ± 0.7                | 12.2 ± 1.2         | 1210 ± 5            |
| 59067.50989 | 6.9 ± 0.5                  | 3.5 ± 0.5          | 1213 ± 5            |
| 59067.53524 | 5.9 ± 0.4                  | 6.8 ± 0.5          | 1202 ± 9            |
| 59069.51499 | 7.6 ± 0.5                  | 5.4 ± 0.2          | 1210 ± 7            |
| 59077.46629 | 6.9 ± 0.4                  | 7.1 ± 0.5          | 1190 ± 4            |
| 59077.46990 | 9.1 ± 0.7                  | 4.5 ± 0.2          | 1180 ± 10           |
| 59077.47533\(^C\) | 7.9 ± 0.4               | 8.9 ± 0.5          | 1217 ± 11           |

\[ \text{Table 1. Scattering times for bursts in Set 1. Burst arrival times are quoted in modified Julian date (MJD) to a precision of about one second, and are referenced to the Solar System barycentre at 1.5 GHz. Scattering times } \tau \text{ were measured using a 2D fitting routine that assumes } \tau \propto \nu^{-4}, \text{ and are referenced to } 1.45 \text{ GHz by the same assumption. The fitting also assumes the Gaussian FWHM is constant across frequency. DMs shown maximize the S/N. Bursts A-D are indicated with superscripts.} \]

\[ \text{Figure 3. Comparison of the narrowest burst with average scattering. a) The dark blue curve shows the frequency-averaged burst intensity vs. time in signal-to-noise units } I(t)/\sigma_{\text{off}} \text{ for burst D, with a time resolution of 0.6 ms. The orange curve shows the result of fitting a Gaussian pulse convolved with an exponential PBF to the burst intensity, which yields a scattering time } \tau = 1.5 \pm 0.4 \text{ ms and a Gaussian standard deviation } \sigma_G = 0.8 \pm 0.2 \text{ ms. The reference frequency } \nu = 850 \text{ MHz is taken to be the highest frequency at which the burst is detected, 1.45 GHz. The filled green region demonstrates the range of scattering tails that would correspond to the same Gaussian width and the range of scattering times measured for other bursts in the sample, normalized to the same peak intensity as the orange model. b) Residuals between the measured burst intensity and the orange and green models shown in panel a). Residuals of } \pm 1 \text{ are indicated by the grey horizontal lines.} \]

\[ \text{3.2 Comparison Between Sets 1 and 2 Bursts} \]

The scattering times shown for individual bursts in Figure 4 represent cases with both sufficient S/N and spectral bandwidth to perform a least-squares fit that yields significant scattering measurements (these bursts constitute Set 1; see Section 2). From these bursts alone, one would infer that the mean scattering time is \( 6.9 \pm 1.0 \text{ ms at 1.45 GHz}, \) and that \( \tau \) can fluctuate by at least a factor of two between bursts. However, bursts in Set 1 only constitute a fraction of the bursts observed, and the scattering variations measured for Set 1 are not necessarily representative of the full range of scattering that may occur. Set 2 contains 32 other bursts, five of which are high S/N bursts that do not show the frequency dependence assumed in the canonical scattering model, either because they are inconsistent with any frequency-dependent temporal broadening or because their temporal widths decrease at lower observing frequencies. The rest of the Set 2 bursts have too low S/N to evaluate the scattering model on an individual burst basis.

In O22, we used Fourier domain stacking of bursts’ temporal profiles (Section 2) to determine a mean scattering time \( \bar{\tau}(1.45 \text{ GHz}) = 9.5 \pm 1.3 \text{ ms} \) for the same burst sample analyzed here. This mean scattering time was obtained using both high and low S/N bursts for which scattering can and cannot be measured individually, and is larger than most of the scattering times shown for Set 1 in Figure 4. This difference is partially due to a trade-off between intrinsic width and scattering: In general, \( \tau \) can only be fit using the canonical scattering model when \( \tau \) is greater than the intrinsic width in at least part of the frequency band. Figure 5 shows the distribution of total widths measured for bursts in Sets 1 and 2. Set 2 does contain more bursts with larger widths than Set 1, but a two-sided Kolmogorov-Smirnov test between the widths of Sets 1 and 2 bursts yields a p-value = 0.4, indicating that the total widths of the two burst sets are statistically consistent with being drawn from the same distribution. We also find no evidence of a strong correlation between burst total width and S/N in either burst set.

In order to assess whether the burst widths in Set 2 do include contributions from scattering, rather than simply having larger intrinsic widths, we examine both the skewness functions of the bursts and re-perform the stacking analysis on Sets 1 and 2 separately.

Using the skewness test, we find that two bursts in Set 2 have skewness functions with significant evidence of scattering, based on both their skewness amplitudes and sign of \( \delta \text{max} \) (see Figure A4 in Appendix A). The skewness test was inconclusive for most of the bursts in Set 2 because their S/N is too low to assess whether their maximum skewness amplitudes are consistent or inconsistent with scattering. Nonetheless, there are 8× more bursts with positive \( \delta \text{max} \) than negative \( \delta \text{max} \) in Set 2, demonstrating that the sample of bursts in Set 2 is largely dominated by positive-handed temporal asymmetries. The distribution of \( \delta \text{max} \) for Set 2 is thus inconsistent with a population of intrinsically symmetric bursts with asymmetries contributed by noise alone. (For reference, all bursts in Set 1 have \( \delta \text{max} > 0 \).) We therefore conclude that bursts in Set 2 are overwhelmingly asymmetric and skewed to positive lags. While we have excluded bursts with identifiable sad-trombone drift from Set 2, we note that even unresolved drifting or an imprecise DM would not necessarily cause bursts to be preferentially skewed to positive lags.

The skewness test indicates that scattering is likely present in Set 2 bursts. We therefore apply the same Fourier domain stacking analysis used in O22 to Sets 1 and 2 separately, in order to determine whether the scattering in Set 2 is significantly different from that in Set 1. The mean and standard deviation of \( \tau \) inferred from this analysis is shown in Figure 4 for both Sets 1 and 2. For Set 1, the stacking analysis...
Figure 4. Burst scattering times and Gaussian widths. Blue points and errors correspond to the best-fit values and 68% confidence intervals for the scattering time $\tau$ in milliseconds at 1.45 GHz (top of the observing band) and the FWHM of the Gaussian burst component, fit using the same procedure as for bursts A-D. Sets 1 and 2 refer to bursts with and without significant least squares fits for $\tau$ and the Gaussian width, respectively. Also shown in orange is the upper limit on $\tau$ for burst D, the narrowest burst in the sample. The grey dashed line and shaded region correspond to the mean and standard deviation of $\tau$ inferred from stacking Sets 1 and 2 together in the Fourier domain (Ocker et al. 2022). The blue and black capped lines indicate the mean of $\tau$ and its standard deviation, inferred from applying the same stacking method to Sets 1 and 2, respectively (Methods).

Figure 5. Distribution of total burst widths. The burst FWHM is defined as $\sqrt{2 \times \text{HWHM}}$ of a burst’s ACF, calculated from the burst profile integrated across the entire frequency band, 1.05 – 1.45 GHz (Methods). Full-widths for bursts in Set 1 (which have individual scattering measurements) are shown in green, and burst widths in Set 2 (no individual scattering measurements) are shown in grey. The average central frequency of the burst emission is 1350 MHz (Methods), and the total widths shown here are consistent with including the contributions of both scattering and intrinsic structure.

yields $\bar{\tau}(1.45 \text{GHz}) = 8.0 \pm 0.7$ ms, whereas for Set 2, the stacking analysis yields $\bar{\tau}(1.45 \text{GHz}) = 11.3 \pm 0.9$ ms. The mean of these values is consistent with the result presented in O22, which found $\bar{\tau}(1.45 \text{GHz}) = 9.5 \pm 1.3$ using both Sets 1 and 2. The mean scattering time inferred for Set 1 from the stacking method is about 1 ms larger than the mean calculated by directly averaging the scattering times of individual bursts in Set 1, although the two methods give results that are technically consistent within one standard deviation. This comparison suggests that the stacking method may overestimate the mean scattering time by an amount comparable to the inferred uncertainties. Simply comparing the mean scattering times for Sets 1 and 2 confirms that $\tau$ varies by at least 40% across the burst sample, but comparing the scattering times of individual bursts in Set 1 to the mean scattering time of Set 2 suggests that $\tau$ can vary by up to 100% or more at 1.45 GHz.

3.3 Summary of Key Results

The difference in $\tau$ between bursts C and D suggests that $\tau$ can vary significantly over a timescale as rapid as 2.9 minutes, and differences in $\tau$ are also seen between bursts detected on different days (Table 1). A significant change in $\tau$ over 2.9 minutes suggests that the length scale over which this change occurs is at most $c\Delta t \sim 0.4$ au, where $c$ is the speed of light. This scale is equivalent to an upper limit on the transverse offset between the two burst LOSs, which trace regions of significantly different scattering strength. This 0.4 au upper limit on the size scale is extremely conservative, given that the actual size scale is probably related to the relative velocity of the source $v \ll c$ (where $v$ is not known a priori). For typical pulsar velocities $\sim 100$ km/s (Verbunt et al. 2017) the size scale would be as small as thou-
of linear polarization increases substantially at higher frequencies (Feng et al. 2022; Anna-Thomas et al. 2022; Dai et al. 2022), suggesting that the non-detection of RM between 1.05 – 1.45 GHz is related to multi-path scattering that reduces the degree of linear polarization (Beniamini et al. 2022; Feng et al. 2022). However, there is no empirical evidence of a direct correlation between the scattering and RM variations, as these phenomena are observed at distinct radio frequencies. Moreover, the large difference in timescales over which the scattering and RM variations are observed (minutes for the former, and days to months for the latter) suggests that these phenomena may arise from separate screens in the CSM.

All of these observations indicate a dynamic, multi-phase source environment. Scattering variations, in particular, imply fluctuations in weakly or non-relativistic, thermal ionized gas along the LOS. In the following section we consider one possible model that explains such fluctuations as a distribution of ionized cloudlets, or “patches,” that are slightly offset from the direct LOS.

5 SCATTERING FROM DISCRETE PATCHES

Here we give an example of a physical model that explains scattering variations in terms of discrete patches distributed near the source. This patch model will be expanded upon in a future paper. This framework can be extended to a range of physical scenarios in which the CSM is non-uniform.

Consider a rotating emission beam whose luminosity is highly intermittent. The burst emission has a duration Δt and a beam width Δθ_b. The spin period of the beam is P_s. The emission beam rotates across a region of depth L, containing scattering patches of radius r_c and total transverse size Δx ≡ 2r_c at typical separations Δl. A scattering patch is located at a distance d_s from the source, and a distance d_l from the observer. The source-to-observer distance d_{so} and lens-to-observer distance d_{io} are both much larger than d_s.

In this model, a single burst would encounter a small number of patches. For simplicity, we assume here just one patch is illuminated. The number density of patches is n_l ~ (Δl)^{-3}. The mean free path for encountering a patch is l_{mfp} = 1/(πn_l r_c^2). In order for a burst to encounter a single patch, l_{mfp} ≲ L, implying an upper limit on the patch number density n_l ≲ 1/(πr_c^2 L). The total number of patches in a spherical volume surrounding the source is then N_l ≲ (4/3) L (r_c L)^{-3}.

There are two main constraints on the beam size Δθ_b: It must be large enough to fully illuminate a patch, implying Δθ_b d_s ≥ Δθ_b L ≥ Δx, and it must be small enough that only one patch is illuminated, implying Δθ_b n_l L^3/3 ~ 1. Taking Δl to be a multiple of m_l of the patch size, we then have Δx/L ≤ Δθ_b ≤ (3/L^2 n_l) ~ 3(m_l/Δx/L)^3, and Δx/L ≥ (1/3m_l). The beam size is thus

$$\Delta \theta_b \leq \left(1/3m_l^3\right)^{1/2} \approx 6 \times 10^{-4} (m_l/100)^{-3/2},$$

where the fiducial value m_l = 100 corresponds to patches that are neither tightly packed nor extremely spread out. With relativistic beaming at a Lorentz factor γ, Δθ_b ≥ 1/γ, implying γ ≤ 1700(m_l/100)^{3/2}. A larger separation between patches increases the upper bound on the Lorentz factor. Lorentz factors ∼ 10^5 have been inferred for radio pulsars (Ruderman & Sutherland 1975), including ∼ 10^4 for Crab giant pulses (bij et al. 2021), which provides one possible metric for comparing the emission mechanisms of FRBs and giant pulses.

The beam duration Δt is also to be minimal that at most one patch is illuminated per spin period P_s. Assuming that the interval between bursts is much larger than P_s, we thus have Δt_c × (2π/P_s) ≤ Δt/L, or Δt_c ≤ Δt P_s / 2π L = m_l Δx P_s / 2π L. For P_s in seconds the emission duration is then

$$\Delta t_c \lesssim 8 \text{ ms} \left(\frac{m_l}{100}\right) \left(\frac{\Delta x}{100 \text{ au}}\right) \left(\frac{P_s}{1 \text{ s}}\right) \left(\frac{1 \text{ pc}}{L}\right).$$

The narrowest burst we detect is 2.9 ± 0.1 ms wide, which points to either smaller m_l, Δx, or P_s, larger L, or some combination of the above. Nonetheless, emission durations on the order of milliseconds are entirely consistent with patches - tens of au in transverse size distributed within a ~ 1 pc wide region around the source. Each patch contributes a DM ~ 2n_e r_c ∼ 4.8 × 10^{-4} pc cm^{-3} (r_c/50 au)n_e. Even for a density ∼ 1 cm^{-3}, this DM would be extremely small compared to the total DM of FRB 20190520B, which may explain why we do not detect any obvious temporal correlations between the observed scattering and DM.

6 SUMMARY & DISCUSSION

We find that scattering times vary between individual bursts from FRB 20190520B. In one case, the scattering time varies by over a factor of two between two consecutive bursts detected 2.9 minutes apart. Such a rapid variation likely arises from plasma inhomogeneities within a parsec of the source on sub-au transverse spatial scales. There is no significant evidence for correlations or trends in the scattering times of individual bursts, or in correlations between scattering and apparent DM variations. These conclusions are ultimately limited by the sparseness of bursts that fit the canonical scattering model (Set 1). We present a methodology based on skewness that can be used in future studies to assess the presence of scattering, even for bursts that do not fit the canonical scattering model. Applying this methodology to Set 2 bursts indicates that scattering is likely present in many of these bursts, even though their individual scattering times cannot be inferred by traditional methods. Subsequent stacking of Set 2 burst profiles yields a mean scattering time t (1.45 GHz) = 11.3 ± 0.9 ms that is about 3 ± 1 ms larger than the mean scattering of bursts in Set 1.

One possible model that can explain the observed scattering variations is a distribution of discrete patches of plasma in the CSM. Conservation of scattered burst flux occurs only for a very wide screen with homogeneous scattering properties. However, a patchy CSM will cause dilution of burst flux in a manner that would likely correlate with scattering (Cordes & Lazio 2001). Patches could also be regions of significantly less scattering than the surrounding volume, and in this case the flux would be diluted except for LOS that pass through the patches. This effect may be difficult to identify in practice, given the large flux variability seen in FRBs for which scatter-broadening appears to be minimal (e.g. FRB 20121102A; Hessels et al. 2019; Li et al. 2021). For FRB 20190520B, we find that Set 2, which includes many low S/N bursts, has a larger mean scattering time than Set 1. However, further assessment of both Set 1 and Set 2 bursts does not yield any significant evidence of a correlation between burst total width and S/N, which would be one indicator of flux dilution from scattering (barring intrinsic flux variations, which are not accounted for). Refraction may also be relevant in the CSM.

Analogous scattering variations have been observed from the Crab pulsar and are induced in its supernova remnant (Lyne & Thorne 1975; Backer et al. 2000; Lyne et al. 2001; McKee et al. 2018). Variations in the diffractive scattering time t have been observed down to a resolution of 15 days over 30 years of archival data, and
show a positive correlation with DM fluctuations \( \leq 0.05 \) pc cm\(^{-3}\) (McKee et al. 2018). Refractive echoes have also been detected over months-long timescales (Backer et al. 2000; Lyne et al. 2001), and coincided with periods where the observed scattering deviated dramatically from the canonical scattering model (Backer et al. 2000; Lyne et al. 2001). Individual, giant pulses from the Crab also show evidence of multiple scattered trains (Sallmen et al. 1999). Changes in the scattering time could be correlated with orbital phase if the FRB source is in a binary system (which is one of the scenarios that could give rise to the large observed RM sign changes). Refraction through a companion outflow could also periodically enhance the burst flux (Johnston et al. 1996; Main et al. 2018). All of these effects have been observed from Galactic pulsars (Johnston et al. 1996; Main et al. 2018; Andersen et al. 2022) and may be observable from FRB 20190520B, although we have not detected them in the data set considered here.

Regardless of the exact physical scenario, FRB local environments may not always yield burst structure consistent with the canonical scattering model typically assumed for burst shapes. Bursts’ temporal structure can deviate from the canonical scattering model for several reasons: The exponential PBF applies to the special case of a Gaussian scattered image, but for non-Gaussian scattered images, the mean scattering delay will be greater than the 1/e time of an exponential PBF (Lambert & Rickett 1999). When the scattering screen is spatially well-confined (such as in a filament or discrete patch), the scattering strength is not uniform in directions transverse to the LOS, and the shape of the scattered image will be influenced by the physical extent of the screen rather than small \( \sim \) au scale plasma density fluctuations (Cordes & Lazio 2001). In this case, the frequency dependence of \( r \) can be significantly shallower than \( r \sim \propto \nu^{-4} \), and the scattering tail will be truncated (Cordes & Lazio 2001). We have identified two high S/N bursts from FRB 20190520B that fall in Set 2 (do not show the frequency dependence expected from canonical scattering), but which have skewness functions with significant evidence of temporal asymmetries that may be related to scattering through a non-uniform screen (these are the bursts shown in Figure A4 in Appendix A). These effects, combined with the degree of variability we have characterized using the canonical scattering model, suggest that scattering may be variable in other FRBs, including as yet one-off FRBs that may not be representative of their source’s local scattering medium, and repeating FRBs that have not yet shown obvious scattering. Scattering variations may be detectable regardless of whether sources also show RM variations and PRSs. Future searches for scattering variations from other repeating FRBs, in addition to correlations between scattering, flux, DM, and polarization, will illuminate how sub-parsec scale processes in FRBs’ local environments shape burst propagation and observed spectra.

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DATA AVAILABILITY

The FAST data used in this paper are available at https://doi.org/10.11922/sciencedb.o00069.00004.

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APPENDIX A: INTERPRETING THE SKEWNESS AMPLITUDE

For noisy pulses with a range of unscattered and scattered widths, the amplitude of maximum skewness \( \kappa_{\text{max}} \) does not have a simple, deterministic relationship with scattering time \( \tau \). We therefore assess whether \( \kappa_{\text{max}} \) for a given burst shows evidence of scattering by comparing the observed \( \kappa_{\text{obs}} \) to the value \( \kappa_{\text{max}} \) would have if the burst were maximally asymmetric; i.e., if the entire burst width were contributed by the PBF. The ratio of maximum skew, \( \frac{\kappa_{\text{max}}}{\kappa_{\text{obs}}} \), is then compared to the ratio that would be obtained for a Gaussian burst with the same observed total width and S/N, \( \frac{\kappa_{\text{max}}}{\kappa_{\text{Gaus}}} \). This comparison of ratios is equivalent to testing whether an observed burst is distinguishable from a Gaussian, to a given level of statistical confidence. Figure A1 shows that the maximum skew ratio \( \frac{\kappa_{\text{max}}}{\kappa_{\text{obs}}} \) is a linear function of S/N. The mean and rms error in this skewness ratio is computed from 500 independent white noise realizations. At high S/N, \( \frac{\kappa_{\text{max}}}{\kappa_{\text{obs}}} \gg \frac{\kappa_{\text{max}}}{\kappa_{\text{Gaus}}} \), because the Gaussian pulse’s skewness is small compared to the skewness of a PBF with the same total width. At low S/N, noise dominates the skewness function, and the ratio

\[ \frac{\kappa_{\text{max}}}{\kappa_{\text{obs}}} \]
observed burst width is roughly $\sigma$ deviation.

The best-fit linear model for $\kappa_{\text{max}}$ vs. S/N, which it reaches unity, depends on pulse width. Figure A1 shows the maximum skewness of the PBF; in this noise-dominated regime, the skewness of a noisy Gaussian pulse becomes indistinguishable from the skewness of the scattering. At low S/N values, noise dominates the skewness, and the maximum skewness for high S/N bursts that have the blue region corresponds to bursts with very small skewness (no scattering).

High S/N bursts that have $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$ approaches unity. In this regime, the skewness function of the noisy Gaussian is indistinguishable from the skewness of an equivalent-width PBF. The slope of $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$ and the S/N at which it reaches unity depend on pulse width. Figure A1 shows the best-fit linear model for $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$ vs. S/N, for a Gaussian standard deviation $\sigma_{\text{Gauss}} = 10$ ms ($\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$). The solid orange line indicates the best-fit linear model, which scales with Gaussian standard deviation as $\sigma_{\text{Gauss}}^{1.1}$. The dashed-dotted line indicates where the skewness ratio equals one. At high S/N values, skewness ratios for observed bursts ($\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$) falling within the blue region correspond to bursts with very small skewness (no scattering).

Figure A2. Intensity, autocorrelation, and skewness functions for a scattered burst. a) Frequency-averaged burst intensity vs. time in S/N units, for Burst A shown in Figure 1. This burst has a measured scattering time $\tau = 6.7 \pm 0.4$ ms at 1.45 GHz. b) Autocorrelation function (ACF) vs. time lag, calculated from the burst profile shown in panel (a). c) Skewness as a function of time lag for the measured burst profile (blue) and the skewness of a one-sided exponential pulse broadening function (PBF) with the same total width as the observed burst (orange). The total width was measured using the ACF. The ratio of the observed maximum skewness to the maximum skewness of the PBF is consistent with a very positively skewed burst (> 95% confidence), as expected from scattering.

In practice, we calculate the ratio of maximum skewness for each observed burst $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$, assuming an exponential PBF that has the same total width as measured from the burst ACF. This ratio is then compared to the simulated mean and rms error of $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$ for the same S/N and total width. We determine whether $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$ falls into one of two relevant regimes:

1. If $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}} \leq 1$ to within 95% confidence (based on the simulated error), the burst skewness falls in the noise-dominated regime, and the presence of scattering is considered indeterminate.

2. If, on the other hand, $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}} > 1$ (to at least 95% confidence), then the burst does not fall in the noise-dominated regime.

In the second case, $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}} > 1$ indicates that the burst skewness is smaller than expected from scattering, whereas $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}} < 1$ indicates that the burst skewness is consistent with scattering, at a given confidence interval based on the simulated error in $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$. Figures A2-A4 show comparisons between the observed skewness and skewness of an equivalent-width PBF for a burst in Set 1 and four bursts in Set 2, which demonstrate cases where the observed skewness is both consistent and inconsistent with scattering. The two bursts shown in Figure A4 are cases where a fit for the canonical scattering model was indeterminate, but both $\kappa_{\text{max}}^{\text{PBF}} / \kappa_{\text{max}}^{\text{Gauss}}$ reveal significant temporal asymmetries that may hint at scattering from a non-uniform medium ($\kappa_{\text{max}}^{\text{obs}}$ is highly skewed to > 99% confidence for the lefthand burst and to 95% confidence for the righthand burst in Figure A4).

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Figure A3. Intensity, autocorrelation, and skewness functions for two bursts without significant skewness. a) - c) Same as Figure A2 for a burst detected at MJD 59061.539. The ratio of the observed maximum skewness to the maximum skewness of the PBF is consistent with skewness dominated by noise (> 95% confidence), and the presence of scattering is indeterminate. d) - f) Same as a) - c) for a burst detected at MJD 59075.454. In this case, the S/N is high but the ratio of observed maximum skewness to the PBF maximum skewness is consistent with very small skewness (> 95% confidence), and the presence of scattering is again indeterminate.

Figure A4. Intensity, autocorrelation, and skewness functions for two bursts with significant evidence of skewness. a) - c) Same as Figure A2a for a burst detected at MJD 59069.501. The ratio of the observed maximum skewness to the maximum skewness of the PBF is close to one, and is inconsistent with the ratio expected for a noisy Gaussian burst (see Figure A1) of the same width at 99% confidence. d) - f) Same as a) - c) for a burst detected at MJD 59075.455. The ratio of the observed maximum skewness is again inconsistent with the ratio expected from a noisy Gaussian of the same width (95% confidence). The canonical scattering model did not yield significant constraints on τ for either of these bursts.