A Highly Variable Magnetized Environment in a Fast Radio Burst Source

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Fast radio bursts are brief, intense flashes of radio waves that arise from unknown sources in galaxies across the universe. Observations of the polarization properties in repeating fast radio bursts have shown they can reside in highly magnetized environments, such as in the immediate vicinity of a recent supernova or massive black hole. We have observed the actively repeating FRB 20190520B over a span of fourteen months and found that its Faraday rotation measure is both large in magnitude and rapidly varying, including two sign changes which indicate time-dependent orientation changes of the magnetic field along our line of sight. The FRB also depolarizes rapidly at lower frequencies. These phenomena can be explained in terms of multi-path propagation through a highly turbulent, dense magnetized screen within a range of 8 AU to 100 pc away from the FRB source, distinctly narrowing the possible physical configurations that could give rise to the emission seen in FRB 20190520B.

One Sentence Summary: An extra-galactic burst of radio waves has line-of-sight magnetic field properties that vary more than any other source observed in the cosmos to date.

Fast radio bursts (1) are an ongoing mystery of the cosmos: we are still developing a broad understanding of what astrophysical conditions can produce them, and what physical mechanisms create their intense flashes. Not only are they bright, but their observed properties imply local astrophysical environments that so far defy a comprehensive theoretical understanding. The magnetization and density of astrophysical plasmas leave strong imprints on FRBs signals that can be used to probe the properties of their environments. Newly discovered FRBs have provided insight into the media (2, 3) and origins (4–6) of these enigmatic sources.

The discovery and localization of FRB 20190520B was recently reported, including its localization to a dwarf host galaxy at cosmological redshift $z = 0.241$ (7). FRB 20190520B
stands out among known FRBs in several properties, including its sustained high repetition rate of $R_{1.2\,\text{GHz}}(> 9.3\,\text{mJy ms}) = 4.5^{+0.9}_{-1.5}\,\text{hr}^{-1}$, its co-location with a compact “persistent radio source” (PRS), and the unusually dense plasma environment near the source. The electron column density $n_e(l)$ as a function of the distance along the line-of-sight $l$ is quantified by the “dispersion measure,” $\text{DM} = \int n_e(l)\,dl$. For FRB 20190520B, the DM is significantly larger than can be attributed to the Milky Way and the intergalactic medium (IGM), which dominate the DM budget of most other FRBs. The rest-frame local contribution to DM is $\text{DM}_{\text{host}} = 902^{+88}_{-128}\,\text{pc cm}^{-3}$ (7), and is around an order of magnitude larger than the average value of inferred FRB $\text{DM}_{\text{host}}$ values, implying a large number of free electrons in FRB 20190520B’s environment (8). In several ways FRB 20190520B is analogous to the first localized repeating source, FRB 121102 (9, 10); it is an active repeating FRB in a low-metallicity dwarf galaxy associated with a PRS. FRB 121102 has an extraordinarily high Faraday rotation measure (RM) (2), but until now the RM of FRB 20190520B had not been measured. The RM quantifies the amount of Faraday rotation of the light integrated along the line-of-sight, given by $\text{RM} \propto \int n_e(l)B_{||}(l)\,dl$, where $B_{||}$ is the component of the magnetic field parallel to the line-of-sight.

We conducted polarimetric observations of FRB 20190520B with the Green Bank Telescope at 1.1-1.8 GHz (hereafter “L-band”) on UTC17-Sep-2020 and at 4-8 GHz (hereafter “C-band”) on three widely-spaced observing epochs (Epoch 1, 14-Sep-2020; Epoch 2, 19,23,27,31-Mar-2021; Epoch 3, 04-Nov-2021), for 6.5 hours in L-Band and a total of $\sim 20$ hours in C-Band. (11) We performed standard threshold-based searching for bursts in this data, including a search of sub-bands to find band-limited emission. In total, we found 9 bursts at L-band, and 16 bursts in C-band above a signal-to-noise ratio (S/N) threshold of 10. We performed standard polarimetric and flux calibration on detected burst segments (11). Our detection rates were $R_{1.4\,\text{GHz}}(> 100\,\text{mJy ms}) = 1.4 \pm 0.4\,\text{hr}^{-1}$ and $R_{6\,\text{GHz}}(> 200\,\text{mJy ms}) = 0.8 \pm 0.2\,\text{hr}^{-1}$ at L and C-bands, respectively. This implies a generally higher event rate (at L-band) than the previous
rate report if we account for our less sensitive fluence threshold.

The profile and burst spectrograms of 12 bursts from our sample is given in Figure S2 and the burst properties of all our bursts are tabularized in Table S2. Like previous detections of repeating FRBs, the total intensity of the detected bursts exhibit band-limited behaviours and time-resolved sub-structure in some pulses. The detected burst bandwidths span an average of 350 MHz at L-band and 850 MHz at C-band.

Our analysis of the full Stokes data shows that the polarization fraction of FRB 20190520B is strongly time- and frequency-dependent, while its RM exhibits unprecedented time-variability. For the five bursts with detected polarization in C-Band, we measured RMs ranging between $2.1 \times 10^3$ rad m$^{-2}$ ($3.2 \times 10^3$ rad m$^{-2}$ in the source frame) and $-24 \times 10^3$ rad m$^{-2}$ ($-36 \times 10^3$ rad m$^{-2}$ in the source frame). This range of RM variability has not previously been observed in astrophysical sources, and spans—in a single target—nearly the full range of RMs observed for any individual pulsar in our galaxy (Figure 1). The highest absolute RM value for FRB 20190520B places it within a factor of three from the RM range of FRB121102.

We observed RM variability on week-long timescales of around $300$ rad m$^{-2}$ day$^{-1}$, and average variability on six-month timescales of the same order. Given the sparsity of the data, it is not yet clear whether the observed changes are fully representative of the full RM range or variability rate for this source, or for instance if this behavior is oscillatory or random-walk in nature. Still, as shown in Figure 2, FRB 20190520B exhibits faster RM variability than other sources studied to date, again with the exception of the RM variation values seen in FRB 121102 (12).

Beyond the large absolute and fractional RM change, one of the most notable features of FRB 20190520B’s RM variations are the two zero-crossings. This observation indicates that some part of the variations in RM are arising from a change in the line-of-sight magnetic field orientation, as opposed to only variance in the electron density or magnetic field strength. To
date, no other astronomical transient source has exhibited zero-crossings and such large absolute \( \text{RM} \) variability. Before we interpret this behavior in detail, however, it is worth noting the radio-frequency-dependent properties of the source.

We corrected the polarization-detected bursts for \( \text{RM} \), and found fractional linear polarization (L/I) between 45–80\% with no significant circular polarization (V/I) in all (with significance defined as greater than five times the standard deviation of off-pulse noise), except for burst C2.1 which demonstrated a V/I of $\sim 42\%$. No L-band bursts exhibit detectable polarization, with the brightest burst having a value of \( L/I \leq 9\% \).

The maximum \( \text{RM} \) we have measured is one and two orders of magnitude less than the \( \text{RM} \) magnitudes that would produce instrumental depolarization in our L- and C-band data, respectively (11). The magnitude and timescale of \( \text{RM} \) variability is not consistent with instrumental depolarization, so we assume that the polarization fraction is intrinsically varying at C- and L band. However, the complete lack of polarization detection in any L-band bursts to date (from this work and other work (13)), despite the greater average S/N of total-intensity detections at L-band, is indicative of an additional extrinsic astrophysical process.

The mean \( \text{DM} \) of FRB 20190520B is $1204.7 \pm 4$ pc cm$^{-3}$ as reported by (7), averaged across a time span of April to September 2020. The mean \( \text{DM} \) in the L-Band is $1206 \pm 0.6$ pc cm$^{-3}$. The mean \( \text{DM} \) in C-Band in the three epochs are (chronologically) $1208 \pm 2, 1205 \pm 1, 1205 \pm 2$ pc cm$^{-3}$. These measurements are all consistent internally and with the previous results, indicating general average stability of \( \text{DM} \) over timescales of months to years. Time and frequency structure in burst intensity make it difficult to trust measured \( \text{DM} \), especially for the S/N-maximizing \( \text{DM} \). Still, we have evidence that \( \text{DM} \) can vary on relatively short timescales, thanks to bright bursts with temporal structure such as burst C3.1 whose S/N was 161. Its structure-maximizing \( \text{DM} \) is roughly $15$ pc cm$^{-3}$ lower than both the mean C-band \( \text{DM} \) and other bright bursts that exhibit temporal structure. Interestingly, C3.1 had the highest absolute
value RM of any burst, despite its lower dispersion.

Under the assumption that the entire $\text{DM}_{\text{host}}$ is local to the region which causes the Faraday rotation, we find the average line-of-sight magnetic field at $\text{RM} = -36 \times 10^3 \text{rad m}^{-2}$ to be $>57 \mu \text{G}$ ($^{11}$). This is a conservative lower limit because it assumes that the electrons generating the detected $\text{DM}_{\text{host}}$ are the same as those contributing to the Faraday screen, and we are only measuring the parallel component of the field. The field can go up to mG if we do not consider the entire $\text{DM}_{\text{host}}$ to be from the Faraday screen. Note, however, that these values are much lower than would be needed to produce Faraday conversion ($^{14, 15}$). If we assume that only the magnetic field orientation changes (that is, the DM and average magnetic field strength are held fixed and $\text{DM}/\text{RM}$ arise from the same region), the observed RM changes could arise in magnetic field strengths of around $B \sim 60 \mu \text{G}$ and line-of-sight orientation changes of $\sim 100^\circ$.

Scattering and scintillation also provide clues to the nature of the local environment. The typical scattering time of FRB 20190520B at 1.4 GHz is $\approx 10 \text{ ms}$ ($^{7}$), roughly one hundred times larger than the upper limit on that of FRB 121102 ($^{16}$). The presence of Galactic scintillation places a constraint on the apparent angular size of the FRB emission, set by the geometry of the screen and source ($^{17}$). In our data we observe scattering at 1.4 GHz and fully modulated Galactic scintillation at both 1.4 GHz and at 6 GHz ($^{11}$). The scattering is likely due to a screen in the host galaxy very near to the FRB-emitting source ($<100 \text{ pc}$) ($^{18}$).

Synthesizing our observations with the known energetic persistent radio source, it is likely that the spectrototemporal and polarimetric properties of FRB 20190520B are caused by material local to the FRB-emitting source. The time- and frequency-dependence of polarization, the large RM and its fluctuations, as well as strong local scattering, can all find a common origin in an interpretation based on propagation through a turbulent and dense magnetoionic plasma screen ($^{19}$). This is in contrast, for instance, to explanations intrinsic to the FRB emission mechanism, or to interpretations arising in a more diffuse pan-galactic origin. In our proposed
scenario, all the effects are imparted in a highly turbulent screen that is made up of sub-eddies or filamentary regions with no preferential magnetic field orientation.

The phenomena of multi-path depolarization and large RM variability are generic to turbulent dynamic and dense magnetoionic plasma environments. However, the magnitude—and therefore observability—of these effects depends on the physical parameters of such a screen. Our observables (the timescale of changes in DM and RM, the local scattering, and the frequency at which light is entirely depolarized) are, in this interpretation, determined by the characteristic size of these eddy regions, the screen depth, and the relative velocities of the FRB source, bulk screen, and internal eddies. Our measurements, combined with a basic model for propagation through such a turbulent screen, constrain the screen to be between 8 AU and 100 pc from the source with a free electron density corresponding to this range in scales of between $5 \times 10^6$ cm$^{-3}$ and 2 cm$^{-3}$, respectively ($I$).

In the methods section of this paper, we explore several scenarios in which such an environment would be local to an FRB source, all resulting in FRB propagation through a magnetized screen. The scenarios we describe include: A) an FRB-emitting neutron star seen through the coronal wind of its binary stellar companion; B) a shocked magnetar wind, where the magnetar itself provides both the FRB and the bulk magnetization. The magnetar wind downstream of the termination shock would give rise to the turbulent screen; and C) an FRB-emitting neutron star in the vicinity of an intermediate-mass black hole with strong outflows ($II$).

Note that this turbulence-based model would imply that the RM and DM variations should obey random-walk variations, with the exception that in any model where the FRB source and screen source are in orbit (e.g. model A and potentially model C), there may be a long-timescale fiducial variation in the average value of RM and DM.

Regardless of the specific physical model for the configuration for FRB 20190520B, the unprecedented RM and DM variations, frequency-dependent polarization, and local scattering
of this FRB’s emissions place strict requirements on the makeup of the FRB 20190520B environment. The origins of the FRB source and environmental screens can be probed in more detail with more frequent and long-term monitoring of the RM and DM variability ranges and timescales for FRB 20190520B, and through measurement of the polarization fraction at radio observing frequencies above 8 GHz.
Figure 1: The distribution of pulsars, magnetars and FRBs in the RM-DM space. The x and y axes are in log space. The thick vertical lines show the range of RM’s observed in these sources. It is clear from the plot that FRB 20190520B shows the most variability.
Figure 2: The time and frequency dependence of FRB 20190520B. The top two panels show its RM and DM variation over roughly one year. We also plot the RMs of other repeating FRBs and the Galactic center magnetar. The bottom panel shows polarisation fraction as a function of frequency, with no polarised detections at 1.4 GHz.
Figure 3: **Linear polarization fraction of the bursts as a function of RM at different MJDs**
The linear polarization fraction is normalized to unity. *Red* shows the burst in Epoch 1, *Blue* shows the detections in Epoch 2 and *Green* shows the detections in Epoch 3.
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Supplementary materials

Supplementary Text
Figs. S1 to S2
Tables S1 to S2
References (20-44)

S1 Observations of FRB 20190520B

S1.1 GBT L-Band

We conducted L-Band observations of FRB 20190520B (16h02m04.266s, -11°17'17.33'') on 17th September 2020 using the 100m Robert C Byrd Green Bank Telescope. The observation was done for a total of 6.5 hours on the source. The L-Band Rcvr1.2 which has a bandwidth of 800 MHz between the range 1100-1900 MHz was used. The VEGAS Pulsar Mode backend recorded 8-bit data across the 800 MHz bandwidth in 4096 channels with a frequency resolution of 195 kHz. The native time resolution of the recorded data was 81.92 μs and the polarization information of the data was in coherence format i.e AABBCRCI. A bright quasar J1445+0958 was observed for flux calibration in both ON and OFF positions.

S1.2 GBT C-Band

Three sets of C-Band observations were done and from here on, we refer to them as Epoch 1, Epoch 2 and Epoch 3.

S1.2.1 Epoch-1

GBT Observations using the C-Band Rcvr4.6 (4-8 GHz) was conducted on 14th September 2020 for a total of 4 hours. A bright quasar J1445+0958 was observed for flux calibration in both ON and OFF positions and a noise diode scan for one minute was done to be used
in calibration of Stokes Parameters. The 8-bit Full Stokes IQUV data was recorded using the VEGAS Pulsar Mode backend across 12288 frequency channels and was sampled with a time resolution of 87.38 $\mu$s and a frequency resolution of 366 KHz.

S1.2.2 Epoch-2

A second set of GBT observations using the the C-Band Rcvr4_6 (4-8 GHz) was done 6 months after the first epoch on March 19th, March 23rd, March 27th and March 31st. The total observing time was 10 hours with 2.5 hours per day. We did a noise diode scan for one minute to calibrate the Stokes parameters and to verify the calibration procedure, we observed a test pulsar B1933+16 prior to observing the source. The 8-bit Full Stokes IQUV data was recorded using the VEGAS Pulsar backend across 12288 frequency channels and was sampled with a time resolution of 43.69 $\mu$s and a frequency resolution of 366 KHz. Note that an independent analyses of Epoch 2 is also reported by (13).

S1.2.3 Epoch-3

We did a third round of observations using the C-Band Rcvr4_6 (3.9-7.3 GHz) on November 4th 2021. A bright quasar 3C286 was observed for flux calibration in both ON and OFF positions. A 5 minute scan on the test pulsar B1933+16 was done prior to the observation of the FRB source. A one minute noise diode scan to do polarization calibration was done on the test pulsar and the FRB source. The 8-bit Full Stokes IQUV data recorded using the VEGAS Pulsar Mode backend across 9216 frequency channels and was sampled with a time resolution of 87.38 $\mu$s and a frequency resolution of 366 KHz.

A brief summary of the all the observations is given in Table S1
Table S1: **List of GBT observation on this source.** The center frequency of the observing band, the frequency and time resolution is also given.

| Observation | Start MJD       | ν₀ (MHz) | Δν (MHz) | Δt (µs) |
|-------------|-----------------|---------|---------|---------|
| L-Band      | 59109.82237270036 | 1400    | 0.195   | 81.92   |
| Epoch 1     | 59106.78295138889 | 6000    | 0.366   | 87.38   |
| Epoch 2     | 59292.43740740741 | 6000    | 0.366   | 43.69   |
|             | 59296.41451388888 | 6000    | 0.366   | 43.69   |
|             | 59300.41737268519 | 6000    | 0.366   | 43.69   |
|             | 59304.41837962963 | 6000    | 0.366   | 43.69   |
| Epoch 3     | 59522.67555555556 | 5637.5  | 0.366   | 87.38   |

S2 **Data Reduction**

We used YOUR (20) to ingest, pre-process the data and search for single pulses. The PSRFITS data were converted to a single total intensity FILTERBANK using your_writer.py. A composite RFI filter, which uses Savgol (21) and Spectral Kurtosis (22) filters with a 4σ threshold and Savgol filter window of 15 channels to identify and mask frequency channels, was applied during the conversion process. The RFI mitigated FILTERBANK was searched for single pulses using your_heimdall.py which runs HEIMDALL (23) on the data. The data was searched in a prior DM range of 1000-1400 pc cm$^{-3}$ and maximum boxcar width of 50 ms. Astrophysical bursts were identified from the resulting candidates using the machine learning classifier FETCH (24) and through manual inspection. L-Band data yielded 9 bursts above $S/N > 10$, the brightest one with a $S/N$ of 75. Some of these bursts were also detected by GREENBURST (25), which is the realtime detection system at GBT. For the C-Band data, we noted that we were missing bursts due to the large observing bandwidth of 4 GHz, combined with the band-limited properties of the bursts themselves. Since most repeaters show band-limited spectral nature (26), we decided to do a sub-banded search on the C-Band data. We divided the total bandwidth into non-overlapping subbands of bandwidth 750 MHz and 1500 MHz, and
then ran the search pipeline mentioned above. This yielded 6, 2 and 8 bursts in Epoch 1, 2 and 3 of the C-Band observations above a threshold of $S/N > 10$.

**S3 Calibration of bursts**

For all bursts in C-Band, we made pulse archives using DSPSR (27) and dedispersed it at the detection DM from HEIMDALL. We then zapped the frequency channels which did not contain the burst using PAZ routine in PSRCHIVE (28). The zapped burst archives were then calibrated for flux and polarization using the PAC routine in PSRCHIVE. The bursts in the Epoch 2 were calibrated only for polarization since a flux calibrator was unavailable for that session.

**S4 Quantifying burst properties**

**S4.1 Rotation Measure**

Rotation measure is defined as the integrated column density of line of sight electrons weighted by the component of the magnetic field along the line of sight.

$$RM = \frac{c^3}{2\pi m_e^2 c^4} \int_0^d n_e(\ell) B_{||}(\ell) d\ell$$  \hspace{1cm} (1)

Extremely large rotation measures can lead to bandwidth depolarization. For finite frequency channel bandwidths $\delta \nu$ at a central observing frequency $\nu_c$, the intra-channel rotation is given by

$$\Delta \theta = \frac{RM c^2 \delta \nu}{\nu_c^3} \text{ rad}$$  \hspace{1cm} (2)

The fractional depolarization is then

$$f_{dpol} = 1 - \frac{\sin(2\Delta \theta)}{2\Delta \theta}$$  \hspace{1cm} (3)

Most repeating FRBs with polarimetry reported on to date are 100% linearly polarized (2, 29, 30). It is therefore a reasonable assumption to assume that FRB 20190520B might intrinsically
(if observed without line-of-sight effects), thus for our observed ∼50% polarization, this implies ∆θ = 1 rad. For our channel bandwidth δν = 0.366 MHz and a center frequency of νc = 6 GHz, we get a lower limit of the RM that can depolarize the signal in C-Band to be 6.5 × 10⁶ rad m⁻². For our L-Band data with center frequency 1.4 GHz and δν = 0.195 MHz, this corresponds to 1.5 × 10⁵ rad m⁻².

Burst profiles were then de-rotated at the respective RM obtained from the RM SYNTHESIS code for each epoch and polarized pulse profile was made by averaging over the frequency dimension. In the presence of noise, Lmeas = √Q² + U² overestimates the total polarization. Therefore, we calculated the unbiased linear polarization (31)

\[ L_{\text{unbias}} = \begin{cases} \frac{L_{\text{meas}}}{\sigma_I} - 1 & \text{if } \frac{L}{\sigma_I} \geq 1.57 \\ 0 & \text{otherwise} \end{cases} \]  

where σI is the off-pulse standard deviation in Stokes I.

S4.1.1 Brute-Force Search

A brute force RM search was done using RMFIT routine of PSRCHIVE. The search was done in a trial RM range of ±10⁶ rad m⁻² which is the maximum RM which can be detected given a frequency resolution of 0.366 MHz, with a step size of 1 rad m⁻². RMFIT does a brute-force search on the given RM range and outputs the RM which maximizes the polarized flux intensity.

S4.1.2 RM Synthesis

In addition to brute-force search, we also performed RM Synthesis (32, 33) on our bursts. RM-Synthesis is an non-parametric approach and is a powerful way of determining the RM of sources using a Fourier like transformation

\[ F(\phi) = \int_{-\infty}^{\infty} P(\lambda^2) \exp^{-2i\phi\lambda^2} d\lambda^2 \]  

where \( F(\phi) \) is called the Faraday Dispersion Function (FDF), \( \phi \) is called the Faraday Depth and \( P(\lambda^2) \) is the total linearly polarized flux intensity. In this method, the source is assumed to be
a sum of emitters at different Faraday depths. Faraday depth is essentially similar to the RM of the source when the emission is not from an extended region and Faraday rotation happens only at one Faraday depth. In the case of FRBs where emission is in the order of millisecond timescale, Faraday depth can be undoubtedly assumed to be equal to the Rotation Measure of the source. RM Synthesis was done using RM-TOOLKIT which performs a 1-D RM Synthesis on the burst data.

Figure S1: The polarized pulse profile of the brightest 4-8 GHz burst (C3.1) in our sample. We find no evidence for RM variation over the pulse, significant circular polarization, nor large polarization position angle (PA) change across the pulse.

The RM values detected for the bursts by both the methods and the polarization fraction obtained by de-rotating the bursts at respective RM, are listed in Table S2. The error reported is the 1σ error on the polarization fraction. For the bursts without an RM detection, we have listed the upper limit of polarization fraction at 0 rad m\(^{-2}\). The values of the RM were then converted

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from the observer’s frame to the source frame, by

\[ RM_{src} = RM_{obs} \times (1 + z)^2 \]  (6)

**S4.1.3 Verifying calibration with test pulsar**

In only Epochs 2 and 3, pulsar PSR B1933+16 was observed adjacent to our observations to serve as an additional test of calibration. Two instances of the pulsar were observed in Epoch 2 (one adjacent to burst C2.1, and the other adjacent to burst C2.2). We verified our calibration and RM search methods by calibrating the test pulsar B1933+16 for Epoch 2 and Epoch 3 using the same procedures applied to the burst data. We measured the RM of the average pulse profile (folding the data using standard software DSPSR at the period of the pulsar), and carried out an RM search using RMFIT and RM TOOLKIT.

In all of the pulsar observations, the polarization and RM properties were internally consistent, and also agreed with the values reported by other work (e.g. (34)). The previously published RM of the pulsar was \( RM = -10.2 \pm 3 \, \text{rad m}^{-2} \) (35). The RMs we detected in the three observations, chronologically, were \( -54 \pm 117\, \text{rad m}^{-2} \), \( -64 \pm 121\, \text{rad m}^{-2} \) and \( -77 \pm 91\, \text{rad m}^{-2} \), respectively. The consistency of these values with one another and with the past published RM value lends confidence in the extreme RM swings we report here for FRB 20190520B.

**S4.2 Dispersion measure**

The mean pulse DM reported for FRB 20190520B is \( 1204.7 \pm 4\, \text{pc cm}^{-3} \) (7). We report the optimized DM of our bursts from GBT observation using two methods:

**S4.2.1 S/N-Maximizing DM**

We use the PSRCHIVE package pdmp to get the DM that maximizes the Signal-to-Noise ratio of the burst. It uses a boxcar matched filtering to compute the S/N. We searched in a DM range
of 1000–1400 pc cm$^{-3}$ with a step size of 0.1 pc cm$^{-3}$. The calibrated pulse archives were given as the input and the burst DM ranges between 1164–1234 with a mean DM of 1206.67 pc cm$^{-3}$ and a standard deviation of 13.55 pc cm$^{-3}$.

**S4.2.2 Structure-Maximizing DM**

Since most repeaters show complex spectro-temporal structure, optimizing the DM which maximizes the structure of the burst can be used to isolate frequency-dependent burst structure from dispersion-based delays (e.g. (36)). In some of the bursts in our sample, such characteristic sub-components which drift in frequency are apparent. Thus, for all bursts with $S/N > 15$, in Table S2 we also report the value of DM which maximizes its structure. We use the package DM_PHASE to get the structure-maximized DM for each burst. The mean structure-maximizing DM across all bursts is 1206.13 pc cm$^{-3}$ with a standard deviation of 11.83 pc cm$^{-3}$, again closely consistent with other burst DM averages in this work and in (7) and (13).

From the DM and RM measurements, we can put initial constraints on the average line of sight magnetic field strength

$$< B_\parallel > = 1.23 \frac{R M}{D M} \mu G \quad (7)$$

Using the range of $D M_{host} = 774–990$ pc cm$^{-3}$, and the range of $|R M_{src}| = 3.2 \times 10^3 – 36 \times 10^3$, we get $< B_\parallel > = 4 – 57 \mu G$.

**S4.3 Detailed Measurements**

A table of the all the detected bursts with its properties is shown in Table S1.

We used BURSTFIT to model the burst profiles of all the bursts (26). We did not model the spectra as it showed a large variety in morphology (see Figure S2) that deviated significantly from the simple Gaussian spectra shape that is traditionally used. We modeled the pulse profiles using a Gaussian function, and used the non-linear least-squares fitting implemented in
`scipy.curve_fit` for fitting. Therefore, we fitted for three parameters: fluence, width and the location of the profile. The modeled parameters and their respective errors are shown in Table S2.

Figure S2: **The burst spectrograms for a subset of bursts in the sample.** The dynamic range of the spectrograms was limited to 3 times the standard deviation of the spectrogram for clarity. Data was decimated in time and frequency for better visualization. The time and frequency resolution of data is shown in the top right of the plot. The burst IDs are given at the top left corner of the plot.
| ID  | MJD          | S/N | $f_{\text{low}}$ (MHz) | $f_{\text{high}}$ (MHz) | $S$ (Jy ms) | $W$ (pc cm$^{-3}$) | $\text{DM}_{\text{snr}}$ (pc cm$^{-3}$) | $\text{DM}_{\text{stru}}$ (pc cm$^{-3}$) | $\text{RM}_{\text{rmmm}}$ (rad m$^{-2}$) | $\text{RM}_{\text{syn}}$ (rad m$^{-2}$) | $L/I$ | $V/I$ |
|-----|--------------|-----|------------------------|-------------------------|-------------|----------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|--------|-------|
| L1  | 59109.875777475(1) | 75   | 1350 1850 1.66(3) 11.7(3) | 1218.3(4) 1199.5(8) | -          | -             | -                                 | -                                 | < 0.09 < 0.02                     |
| L2  | 59109.9843406799(5) | 47   | 1600 1850 0.95(2) 4.2(1)  | 1202.0(2) 1214.0(1) | -                                  | -               | -                                 | -                                 | < 0.11 < 0.05                     |
| L3  | 59109.880862127(2) | 20   | 1550 1850 0.36(2) 5.4(4)  | 1207.7(3) 1218.0(2) | -                                  | -               | -                                 | -                                 | < 0.18 < 0.11                     |
| L4  | 59109.9290786082(8) | 19   | 1450 1850 0.24(1) 2.3(2)  | 1203.5(2) 1215.03(8) | -                                  | -               | -                                 | -                                 | < 0.19 < 0.14                     |
| L5  | 59110.042060525(2) | 15   | 1450 1850 0.2(2) 3.4(4)  | 1201.7(4)  | -                                      | -               | -                                 | -                                 | < 0.3 < 0.14                     |
| L6  | 59110.043763417(5) | 12   | 1650 1850 0.28(3) 9(1)   | 1218.7(8)  | -                                      | -               | -                                 | -                                 | < 0.5 < 0.4                      |
| L7  | 59109.8633426(2)   | 11   | 1650 1850 0.4(5) 23(3)   | 1203.0(2)  | -                                      | -               | -                                 | -                                 | < 0.6 < 0.5                      |
| L8  | 59109.943612607(2) | 10   | 1450 1850 0.16(2) 3.7(5)  | 1195.0(5)  | -                                      | -               | -                                 | -                                 | < 0.9 < 0.2                      |
| L9  | 59109.855793956(4) | 10   | 1350 1850 0.19(2) 6.0(9)  | 1211.9(8)  | -                                      | -               | -                                 | -                                 | < 0.6 < 0.3                      |
| C1.1| 59106.8939062428(3) | 17   | 4123 4500 0.49(2) 0.96(5) | 1209.0(2) 1189.0(2) | -                                  | -               | -                                 | -                                 | < 0.22 < 0.06                    |
| C1.2| 59106.8690704835(9) | 16   | 4160 4500 0.56(4) 2.4(2)  | 1179.0(3) 1190.0(10) | -                                 | -               | -                                 | -                                 | < 0.4 < 0.16                    |
| C1.3| 59106.9057759794(3) | 15   | 4353 4610 1.26(4) 1.8(7)  | 1208.0(2)  | -                                      | -               | -                                 | -                                 | < 0.16 < 0.03                    |
| C1.4| 59106.9034483384(3) | 11   | 4160 4500 0.39(2) 0.92(7) | 1203.0(1)  | -                                      | -               | -                                 | -                                 | < 0.21 < 0.11                    |
| C1.5| 59106.909608189(2)  | 10   | 4160 4500 0.54(5) 3.6(4)  | 1234.0(5)  | -                                      | -               | -                                 | -                                 | < 0.4 < 0.1                      |
| C1.6| 59106.790923985(6)  | 10   | 5500 6000 0.2(2) 1.1(1)  | 1217.0(2)  | -                                      | -               | -                                 | -                                 | < 0.4 < 0.1                      |
| C2.1| 59292.453781287(5) | 17   | 4500 5250 0.34(2) 1.36(9) | 1207.0(1) 1200.0(0) | 3800.0(0) 3700.0(0) | 0.6(1) 0.42(7) | -                                 | -                                 | < 0.16 < 0.03                    |
| C2.2| 59300.4699331622(5) | 18   | 4117 6750 0.36(1) 2.17(9) | 1204.0(1) 1220.0(0) | 2400.0(0) 2100.0(10) | 0.45(6) 0.13(2) | -                                 | -                                 | < 0.16 < 0.03                    |
| C3.1| 59522.71375078164(8) | 161  | 4133 5450 3.97(3) 2.02(2) | 1208.0(1) 1192.0(3) | -24034.5(7) -24010.0(10) | 0.82(1) 0.06(7) | -                                 | -                                 | < 0.2 < 0.19                    |
| C3.2| 59522.6990176385(4) | 19   | 4133 5450 0.27(1) 1.41(9) | 1206.0(1) 1215.0(2) | -                                 | -               | -                                 | -                                 | < 0.2 < 0.11                    |
| C3.3| 59522.7151483105(4) | 18   | 4324 5450 0.21(1) 1.15(9) | 1218.0(2) 1213.0(2) | -                                 | -               | -                                 | -                                 | < 0.2 < 0.11                    |
| C3.4| 59522.780081665(1)  | 13   | 3950 5450 0.19(2) 2.1(2)  | 1220.0(3)  | -                                      | -               | -                                 | -                                 | < 0.5 < 0.3                      |
| C3.5| 59522.8924164286(5) | 11   | 5825 6575 0.12(1) 0.7(1)  | 1164.0(1)  | -                                      | -               | -                                 | -                                 | < 0.4 < 0.2                      |
| C3.6| 59522.706006769(1)  | 10   | 3950 5075 0.23(2) 2.6(3)  | 1213.0(5)  | -                                      | -               | -                                 | -                                 | < 0.3 < 0.3                      |
| C3.7| 59522.7144852698(8) | 10   | 4325 5075 0.17(2) 1.3(2)  | 1197.0(2)  | -                                      | -               | -                                 | -                                 | < 0.4 < 0.2                      |
| C3.8| 59522.690850195(1)  | 10   | 5075 5825 0.17(2) 1.5(2)  | 1219.0(3)  | -                                      | -               | -                                 | -                                 | < 0.4 < 0.2                      |
Table S2: Properties of all L and C Band bursts of FRB 190520. The MJDs reported are barycentred and are referenced to infinite frequency. S/N is the detection signal-to-noise reported by the single pulse search software. $f_{\text{low}}$ and $f_{\text{high}}$ are the minimum and maximum frequency extent of the bursts, determined visually. S is the fluence of the burst. W is the width in milliseconds. $DM_{\text{snr}}$ is the S/N maximizing DM and $DM_{\text{stru}}$ is the structure maximizing DM. $RM_{\text{rmfit}}$ are the RM values reported by RMFIT and $RM_{\text{syn}}$ are the RM values as reported by RM TOOLKIT. L/I is the fractional linear polarization and V/I is the fractional circular polarization; upper limit is reported for non-detections at RM = 0 rad m$^{-2}$. 

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S5 Scattering and scintillation

The pulse intensity is fully modulated, indicating that it is resolved by a scattering screen in the Milky Way. We fit a Lorenzian to the autocorrelation (ACF) function of our brightest bursts and find a decorrelation bandwidth of $\Delta \nu \approx 35\pm 1$ MHz. This is consistent with our 1.4 GHz measurement of scintillation ($\Delta \nu \approx 0.5$ MHz) and previous measurements (7, 18), as well as the predicted value (37). The presence of Galactic scintillation and temporal scattering suggest a local origin of the latter, as the Milky Way’s screen would resolve the scattered pulse if the screen were in an intervening galaxy because angular broadening would be too large (17).

S6 Comparison with other astrophysical sources

RM variations have been reported in other FRBs and in the Galactic center magnetar J1745–2900. FRB 121102 has been reported to have a decreasing trend in RM, varying about 200 rad m$^{-2}$ day$^{-1}$. It also shows short time scale variations of $\sim 10^3$ rad m$^{-2}$ week$^{-1}$. This decrease was interpreted by the model of an expanding nebula near a supernova remnant (12), but the exact origin remains unclear. FRB 20201124A also shows irregular short term variation in RM followed by a period of steady RM (3). This source also shows RM variation within burst duration. Another interesting source that shows variation in RM is the Galactic center magnetar J1745–2900 (38, 39). It shows a variation of about 7.4 rad m$^{-2}$ day$^{-1}$ in spite of small DM changes. This variation is attributed to variation in projected magnetic field along the line of sight of the rapidly rotating magnetar. Interestingly, this source also depolarizes rapidly at low frequencies (39).

S7 Interpretation

The spectral dependence of the polarization, the strongly fluctuating values of RM, and the strong scintillation (characterized by a relatively large scattering time) measured at the L band
can all be naturally understood in the context of multi-path propagation. We demonstrate below that it is indeed possible to have a screen with physically plausible parameters that satisfies the various observational constraints simultaneously. The general idea is as follows. Strong scintillation implies that the diffraction scale of the screen (over which the phase of an incoming wave changes by order unity) is very small relative to the Fresnel radius. At the same time, the size of patches over which the PA changes by order unity, \( \ell_\chi(\nu) \), is expected to be much larger (19). If \( \ell_\chi(\nu) \) is of order the refractive scale (i.e. the observable size of the screen) at some \( \nu_{\chi s} \), then above this frequency the polarization will remain large (and there will be little circular polarization) while at lower frequencies the polarization will be strongly reduced (and there will be circular polarization on the order of tens of percent of the linear polarization). The observed depolarization at L band, combined with the order unity polarization measured at C band and the strong upper limits on the circular polarization component at the latter band, suggest therefore \( \nu_{\chi s} \sim 5 \text{GHz} \). Finally, the variability of RM by \( \sim 300 \text{rad m}^{-2} \) over a scale of less than around one week will dictate the size of the \( \ell_\chi \) patches.

The first constraint on the screen properties comes from the measured fluctuations in RM and DM between different bursts. Attributing these differences to the properties of the fluctuating screen we can estimate \( B_{||} \approx 1.2 \Delta \text{RM}_4 \Delta \text{DM}_1 \text{mG} \) and \( L \approx 10 n^{-1} \Delta \text{DM} \text{pc} \) where \( B_{||} \) is the component of the magnetic field within the screen parallel to the line of sight, \( L \) is the size of the screen, \( n \) is the particle density and \( \Delta \text{RM}_4 \equiv \Delta \text{RM}/10^4 \text{rad m}^{-2}, \Delta \text{DM}_1 \equiv \Delta \text{DM}/10 \text{pc cm}^{-3} \). All other properties of the turbulent screen can be prescribed given two more physical quantities: \( d, l_{\text{max}} \) (respectively describing the distance of the source to the screen and the largest turbulent eddy size) and one final quantity, \( v_{\text{max}} \) (the maximum between the eddies’ turnover velocity and the velocity of the screen relative to the line of sight) the value of which is much better constrained apriori, and is expected to be \( \sim 10^2 \text{ -- } 10^3 \text{km s}^{-1} \). There are then
three additional observational constraints: (i) the scattering time measured at L band\(^1\) \(\nu_{\chi, s} \sim 5\,\text{GHz}\) (see above) and (iii) \(\ell_{\delta\text{RM}, 2.5}/v_{\text{max}} < 1\) week (where \(\ell_{\delta\text{RM}, 2.5}\) is the scale over which the screen RM changes by 300 rad m\(^{-2}\) and \(\ell_{\delta\text{RM}} = (\delta\text{RM}\lambda^2)^{6/5}/\ell_{\chi}\)). These conditions can be re-written as

\[
\frac{L}{\ell_{\text{max}}} < 1.6 \times 10^7 \nu_{\text{co,2}}^{-5/4} \Delta\text{DM}_1^{-7/4} n_1^{-5/4}
\]

(8)

\[
\frac{L}{\ell_{\text{max}}} = 5 \times 10^8 \left(\frac{d}{L}\right)^{5/4} \nu_{\chi,s,5\,\text{GHz}}^{23/4} \Delta\text{DM}_1^{-1/4} \Delta\text{RM}_4^{-3/2} n_1^{-5/4}
\]

(9)

\[
\frac{L}{\ell_{\text{max}}} > 1.5 \times 10^6 \text{DM}_1^{5/2} \Delta\text{RM}_4^{-3} n_1^{-5/2} v_{\text{max,7}}^{-5/2} t_w^{-5/2} \delta\text{RM}_{2.5}^{-3}
\]

(10)

where \(\nu_{\text{co,2}} \equiv \nu_{\text{co}} = 100\,\text{Hz}\) (\(\nu_{\text{co}}\) is the decorrelation bandwidth inferred at L band), \(\nu_{\chi,s,5\,\text{GHz}} \equiv \nu_{\chi,s}/5\,\text{GHz}\), \(n_1 \equiv n/10\,\text{cm}^{-3}\), \(v_{\text{max,7}} \equiv v_{\text{max}}/10^7\,\text{cm}\,\text{s}^{-1}\), \(t_w \equiv t/1\) week and \(\delta\text{RM}\) is the fluctuation in the RM on the timescale \(t_w\). A range of solutions for these equations exist as long as \(2\,\text{cm}^{-3} < n < 5 \times 10^6\,\text{cm}^{-3}\), \(8\,\text{AU} < d < 100\,\text{pc}\), \(20 < d/L < 3 \times 10^4\). For such a screen we predict a spectral dependence of the polarization scaling as \(\nu^{1.7}\) below \(\approx 1.5\,\text{GHz}\) (with a slightly steeper dependence between this frequency and \(\nu_{\chi,s}\), which is indeed consistent with the observed polarization change between the L and C band). Alternatively, at frequencies higher than the C band, we expect the depolarization to become negligible. Polarization measurements at such frequencies could reveal the true polarization behaviour of the source. Finally, we note that the timescale associated with stochastic changes in the polarization angle and the intensity due to the scintillating screen, is related to the motion relative to the line of sight of the diffraction scale (40). The latter can be many orders of magnitude smaller than \(\ell_{\chi}\). For the same parameters as above, this timescale is \(10^{-4} < t_{\text{var}} < 10^{-1}\) s.

What could be the origin of such a screen? We discuss below three possible physical origins for such a screen.

**Shocked NS wind.** One interesting possibility is that the central object is a magnetized NS

\(^1\)This is strictly an upper limit on the scattering time associated with the magnetized screen accounting for depolarization, as it is possible that the screen dominating the scintillation is physically distinct from the former.
and that the magnetized screen is provided by the shocked NS wind that lies downstream of the termination shock. The magnetic field in this scenario can be supplied by the central NS. The required $B \approx 1 \text{ mG}$ implies a screen distance of $d_B = B_{NS} R_{NS}^3 \Omega^2 / (Bc^2)$ where $B_{NS}, R_{NS}$ are the magnetic field of the NS and its radius and $\Omega$ is the NS spin frequency. We have also assumed that the field decays as a dipole at large distances up until the light cylinder, beyond which $B \propto r^{-1}$. A necessary condition is that the required radius fall above the termination shock, $r_s \approx \sqrt{B_{NS}^2 R_{NS}^6 \Omega^4 / (4\pi P c^4)}$ (where $P$ is the ram pressure). The requirement $d_B > r_s$ is independent of the NS properties, and depends only on the ratio of energy densities at the termination shock: $d_B/r \approx 4\pi P / B^2$. For $B = 1 \text{ mG}$, it translates to $P > 8 \times 10^{-8} \text{ erg cm}^{-3}$, which can be readily satisfied in an ISM environment for reasonable values of the NS proper velocity and the ISM external density. A major obstacle for this scenario is that the shocked NS wind is typically too tenuous to provide the measured $\Delta \text{DM}$. As an example, for $B = 10^{14} \text{ G}, \Omega = 100 \text{ Hz}, d_B \approx 0.4 \text{ pc}$. At this location the density of the shocked wind powered by the spindown luminosity is $n \sim 4 \times 10^{-3} \gamma_w^{-2} d_{pc}^{-2} \text{ cm}^{-3}$ where $\gamma_w$ is the Lorentz factor of the wind (which may be much greater than unity). The excess DM that this wind can provide is therefore $< 2 \times 10^{-4} \text{ pc cm}^{-3}$, much too small compared to the observed value. Furthermore, note that we have assumed here an electron-positron plasma which maximizes the density for a given luminosity, but also implies no Faraday rotation (and therefore no depolarization by the screen). So for such a wind to provide a viable screen there must be some baryon loading in the flow, which will further reduce the estimated density. One possible way out would be to power the shocked density wind by episodic mass ejections from the neutron star. Such mass ejections are known to occur in giant flares from magnetars, and can contribute a much greater density (and the needed baryons) to the shocked wind. This situation relies on the magnetar having gone through a giant flare at a time $\sim d/c$ prior to the present day, which for the numeric example above is on the order of years. A second possibility that does not rely on such mass
ejections in the recent past can arise if the magnetar shocked wind is mixing at the contact discontinuity with the shocked CSM above it (e.g. due to Rayleigh-Taylor instability). If such mixing occurs efficiently, the shocked CSM can provide the required large density, while the shocked wind provides the relatively strong magnetic field. Finally we note that if the NS is sufficiently young, the surrounding material that the wind is pushing into may be dominated by the supernova remnant, which can enhance its density significantly.

**Binary wind.** A second possibility, that is independent of the nature of the compact object, is that the compact object has a binary companion with a strong wind. In this case the distance of the screen can be of order the separation of the two stars, and can probe the lower end of the allowed $d$ range quoted above. Taking $d \approx 10$ AU, the requirement for the density becomes $n \approx 5 \times 10^6$ cm$^{-3}$, corresponding to a mass loss rate of $\dot{M} \approx 3 \times 10^{-8} M_\odot$ yr$^{-1}$ with a wind velocity of $v_w \sim 10^3$ km s$^{-1}$. Such a mass-loss rate is superseded by many observed stars, and is therefore certainly plausible. While the wind from the binary can be turbulent, and the properties of the screen may change quasi-randomly on short timescales, a prediction of the binary wind scenario is that there should be an underlying periodicity to the observed screen properties with the orbital period of the binary. An advantage of this scenario is that it can naturally account for the observation that the excess DM appears to be decreasing in the same time interval during which the excess RM is increasing, as long as the magnetic axis is misaligned relative to the binary orbital spin. However, at a separation of $\sim 10$AU, that period is $\sim 100(M_{\text{tot}}/10M_\odot)^{-1/2}$yr, way too long to be observed in the foreseeable future.

**Material around a massive black hole** A close Galactic analog to FRB 20190520B and FRB 121102 is the radio-loud magnetar J1745–2900, which resides just 0.12 pc from Sgr A* (38). Its RM is large and highly variable (39) and its DM is large but relatively stable, indicating that RM variation is likely due to changes in the magnetic field geometry. It is also depolarized at low frequencies and strongly scattered. If the compact persistent radio source
(PRS) associated with FRB 20190520B were due to an intermediate mass black hole (IMBH), the surrounding material may account for the FRB’s time- and frequency-dependent polarization effects. The prompt radio emission could be produced by a nearby neutron star (41), as with J1745–2900, or even by the accretion disk itself (42–44).

An IMBH accreting close to, or even beyond the Eddington limit will drive powerful outflows. The density of the outflow at some distance \( d \) can be estimated as \( n_w \approx \dot{M}_w / (4\pi d^2 v_w) \approx 2(M/M_\odot) f_M d_{15}^{-2} v_{w,0.1c}^{-1} \text{ cm}^{-3} \), where \( \dot{M}_w \) is the wind outflow rate, we have defined \( f_M \equiv \dot{M}_w / \dot{M}_{\text{edd}} \) and assumed a wind velocity of \( v_w \approx 0.1c \). Considering the constraint \( d/L \geq 20 \), the observed excess DM of the screen can be reproduced if the screen is placed at a distance \( d < 3 \times 10^9 (M/M_\odot) f_M \text{ cm} \). Imposing the condition \( d > 10\text{AU} \), we find \( M > 5 \times 10^4 M_\odot f_M \).

We note that in the case of FRB 121102, a multi-wavelength analysis of the associated PRS concluded that it was more likely to be a neutron star wind nebula than an AGN. A similar approach to the FRB 20190520B PRS, including K- and Ku-band radio observations, H\( \alpha \) emission line analysis, and X-ray constraints, could rule out or support the IMBH scenario.