A repeating FRB in a dense environment with a compact persistent radio source

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Fast radio bursts (FRBs) are the most energetic radio transients in the Universe, the central engines of which remain unknown and could be diverse. The dispersion sweeps of FRBs provide a unique probe of the ionized baryon content of the intergalactic medium\(^1\) as well as FRBs’ natal environments\(^2\). Here we report the discovery and localization of a new active repeater, FRB 190520B, which is co-located with a compact, persistent radio source (PRS) and identified with a dwarf host galaxy of high specific star formation rate at a redshift \(z = 0.241\). The estimated host galaxy dispersion measure (DM) \(\text{DM}_{\text{host}} \approx 902^{+88}_{-128}\) pc cm\(^{-3}\) is nearly an order of magnitude higher than the average of FRB host galaxies\(^3, 4\) and much larger than those of the intergalactic medium, suggesting caution in inferring redshifts for FRBs without accurate host galaxy identifications. This represents the second source after FRB 121102\(^5\) with a confirmed association between a FRB and a compact PRS. The dense, complex host galaxy environment and the associated persistent radio source may point to a distinctive origin or an earlier evolutionary stage for active repeating FRBs.

FRB 190520B (corresponding TNS name FRB 20190520B, same hereafter) was discovered with the Five-hundred-meter Aperture Spherical radio Telescope (FAST)\(^6\) in drift-scan mode as part of the Commensal Radio Astronomy FAST Survey (CRAFTS)\(^7\) at 1.05–1.45 GHz in 2019. Four bursts were detected during the initial scan, suggesting a repeater. Monthly follow-up tracking observations between 2020 April and 2020 September detected 75 bursts in 18.5 hrs with a mean pulse dispersion measure (DM) of 1210.3 ± 0.8 pc cm\(^{-3}\). Assuming a Weibull distribution of the burst waiting time, we model the FRB burst rate to be \(R(> 7\sigma) = 4.5^{+1.9}_{-1.5}\) hr\(^{-1}\), making it an
active repeater. Similar to other repeaters, this FRB shows complex frequency-time structure, with frequency modulation, multi-component-profiles, sub-burst drifting, and scattering (Figure 1 and Methods).

We observed FRB 190520B with the Karl G. Jansky Very Large Array (VLA) using the real-fast fast transient detection system\textsuperscript{10}. Throughout the second half of 2020, we observed the source for 16 hours and detected 3, 5, and 1 bursts in bands centered at 1.5 GHz, 3 GHz, and 5.5 GHz, respectively. We measured a burst source position of (RA, Dec) [J2000] = (16h02m04.266s, $-11^\circ 17' 17.33''$) with position uncertainty (1$\sigma$) of (0.09'', 0.10'') dominated by systematic effects. Deep images using data from the same observing campaign reveal a persistent, radio continuum counterpart at (RA,Dec) [J2000] = (16h02m04.259s, $-11^\circ 17' 17.38''$) with 1$\sigma$ position uncertainty of (0.09'', 0.10'') and flux density of 202 $\pm$ 8 $\mu$Jy at 3.0 GHz. Using the average flux density of each sub-band over the VLA campaign, we find that the radio continuum counterpart spectrum can be fit with a powerlaw with index $-0.41\pm0.04$.

Figure 2 shows the FRB location compared to deep optical, near-infrared (NIR) and radio images of the field. The optical image ($R'$-band) obtained by CFHT/MegaCam reveals a galaxy (J160204.31--111718.5) at the location of the FRB, the light profile of which peaks at $\sim$ 1'' south east. Given the measured offset 1.3'' of the FRB from the galaxy and the density of galaxies with this magnitude, we estimate a chance coincidence probability of 0.8%\textsuperscript{11}(see Methods), supporting the claim that J160204.31--111718.5 is the host galaxy of FRB 190520B. The NIR image ($J$-band, 1.153-1.354 $\mu$m) obtained by Subaru/MOIRCS\textsuperscript{12} shows the most likely stellar component of
J160204.31−111718.5 with an AB magnitude of 22.1±0.1 in J-band, with FRB 190520B and the radio continuum counterpart on the galaxy periphery.

We obtained an optical spectrum at the location of the FRB with the Double Spectrograph on the Palomar 200-inch Hale Telescope which revealed the redshift of the putative host to be z = 0.241 based on a detection of strong Hα, [O III] 4859Å, and [O III] 5007Å lines (see Methods). A follow-up observation with the Low Resolution Imaging Spectrometer (LRIS) at the Keck I Telescope covering both the FRB location and the nearby Subaru J-band source along the extended R′-band structure indicates the R′-band structure is dominated by the [O III] emission at the same redshift of z = 0.241. The Hα luminosity \( L_{H\alpha} = 7.4 \pm 0.2 \times 10^{40} \text{ erg sec}^{-1} \) after extinction correction suggests a star formation rate of \( \sim 0.41 \text{ M}_\odot \text{ yr}^{-1} \). Based on the J-band magnitude, we estimate the stellar mass of the host galaxy to be \( \sim 6 \times 10^8 \text{ M}_\odot \). Thus, we characterize J160204.31−111718.5 as a dwarf galaxy with a relatively high star-formation rate for its stellar mass compared with the local SDSS galaxies\(^{14,15}\). At the luminosity distance 1218 Mpc implied by the redshift, the radio continuum counterpart has a spectral luminosity of \( L_{3 \text{ GHz}} = 3 \times 10^{29} \text{ erg cm}^{-1} \text{ Hz}^{-1} \).

It is usually assumed that the redshift of a FRB source can be estimated from the DM attributed to the intergalactic medium (IGM), \( \text{DM}_{\text{IGM}} = \text{DM}_{\text{FRB}} - \text{DM}_{\text{host}} - \text{DM}_{\text{MW}} \). Theoretical calculations\(^{16}\) and observations\(^{11}\) have independently estimated the IGM contribution to FRB DM as a function of redshift (Figure 3). For a DM contribution from the Milky Way of 113 ± 17 pc cm\(^{-3}\) (including a ±20% error in the NE2001 estimate\(^{11}\) for the disk contribution and a flat halo distribution from 25 to 80 pc cm\(^{-3}\)) combined with an assumed host galaxy DM of only 50
pc cm$^{-3}$, the implied redshift range for FRB 190520B is $z \sim 1$ to 1.6 (for baryon fractions $f_{\text{IGM}}$ of 0.6 to 1 for the ionized IGM), much larger than the measured value (see Methods).

Instead, using $\text{DM}_{\text{IGM}}(z = 0.241) \approx 195^{+110}_{-70}$ pc cm$^{-3}$ (68% interval to account for cosmic variance of $\text{DM}_{\text{IGM}}$ and 0.85 for the ionized baryon fraction [13]) combined with the Milky Way contribution, a very large host DM (disk + circumgalaxy + local to source contribution) of $\text{DM}_{\text{host}} = 902^{+88}_{-128}$ pc cm$^{-3}$ is implied. Increasing the ionized fractions from 0.6 to 1 expands the range from 740 to 1020 pc cm$^{-3}$.

In addition to the extremely low chance coincidence probability, the measured DM and scattering properties of FRB 190520B exclude the possibility that J160204.31$-$111718.5 is a foreground galaxy with the true FRB host much further in the background. The observed H$\alpha$ emission allows a range for the DM contribution of the galaxy in the observer frame of 346 to 1212 pc cm$^{-3}$ for temperatures from $0.5 \times 10^4$ to $5 \times 10^4$ K (see Methods). The scattering contribution of a foreground galaxy depends not only on its DM contribution but also on the geometric leverage effect, which will increase the scattering by several orders of magnitude relative to scattering in the host galaxy. If J160204.31$-$111718.5 were a foreground galaxy, the allowed range of scattering times would be 0.6 to 32 s at 1.25 GHz, orders of magnitude larger than the observed mean scattering time of $9.8 \pm 2$ ms (see Methods).

The observed scattering time is thus far too small for the proposed host galaxy to lie in the foreground, consistent with the low chance coincidence of FRB 190520B with J160204.31$-$111718.5.
Both methods for estimating $\text{DM}_{\text{host}}$ for FRB 190520B demonstrate that the distribution of $\text{DM}_{\text{host}}$ values can have a long tail, which may add considerable variance to estimates for the IGM contribution. It is also more likely that FRBs with large $\text{DM}_{\text{host}}$ will not be detected by search systems sensitive to a limited DM range. A large sample of FRBs will allow the host galaxies, their circumgalactic media, and near-source environments to be probed statistically along with the IGM.

The co-located radio continuum counterpart, the star-forming dwarf host galaxy, and the high repetition rate, make FRB 190520B a clear analog to FRB 121102, the first repeating FRB\textsuperscript{19} and the first to be identified with a compact, luminous PRS\textsuperscript{5, 24} ($L_\nu \approx 3 \times 10^{29} \text{ erg s}^{-1} \text{ Hz}^{-1}$). Another repeating source, FRB 20201124A, was also associated with a radio continuum counterpart\textsuperscript{20, 22}. However, through optical spectroscopy and radio interferometric measurements, it was demonstrated that the persistent radio emission was spatially extended and consistent with radio emission associated with star formation in the host galaxy\textsuperscript{23}. If the radio continuum counterpart to FRB 190520B is from star formation, however, its luminosity would imply a star-formation rate of $\sim 10 \ M_\odot \text{ yr}^{-1}$, a factor of 25 larger than that measured for the host galaxy and a factor of five larger than highest observed star formation rate for galaxies of this mass\textsuperscript{14}. Given its extreme luminosity, unresolved structure in VLA observations, and offset from the center of the optical emission of the host galaxy, we conclude that the radio continuum counterpart is a compact source that is physically connected to FRB 190520B, a true PRS. The whole properties of FRB 190520B could be found in Table .
Various methods have been used to argue that repeating and non-repeating FRBs comprise different subclasses\textsuperscript{25,26,37}, either at different evolutionary phases or entirely different physical scenarios. While the observed burst repetition and morphology can be temporal due to various mechanisms\textsuperscript{27}, PRS emission and DM\textsubscript{host} reflect more persistent aspects of the FRB environment and thus may be more reliable tracers of any putative subclasses.

Prior to FRB 190520B, more than a dozen FRBs had been localized, including five repeating sources\textsuperscript{28,29}, but only FRB 121102 had been found to be associated with a compact PRS. The two FRBs associated with PRSs are active (e.g. a peak burst rate of 122 hr\textsuperscript{−1} has been found for FRB 121102\textsuperscript{30}) and have large DM\textsubscript{host} values, implying that such features could require dense, magnetized plasma within parsecs of the source of the bursts\textsuperscript{9,31}. Burst activity may then be correlated with the relativistic plasma emitting synchrotron radiation and the presence of thermal plasma in the local FRB environment. The nature of that correlation is plausibly related to FRB formation (e.g., a newborn source in a young supernova remnant or relativistic wind nebula), suggesting that highly active repeaters, such as FRB 121102 and FRB 190520B, are “newborns”, which still reside in their complex, natal environments\textsuperscript{31,32}. Some active repeaters do have comparably strict limits on PRS counterparts\textsuperscript{33,34}, which suggests complexities in the connection between burst activity and PRS and/or diversity among repeaters. A luminous PRS may require a special environment around the source or it might be an evolutionary effect. A plausible scenario could be, as the source ages, the PRS fades, the event rate drops, and the surrounding plasma dissipates\textsuperscript{35}.

The discovery of FRB 190520B and its high similarity to FRB 121102 suggest that there
may be some useful correlations between burst activity, the presence of a persistent radio source, and other properties. Our results signify a wider range of host-galaxy DMs need to be considered for constraints on cosmic baryons in the IGM. Further study of such correlations may help identify outliers to the Macquart relation and potentially help calibrate biases. More such detections in the near future will also further clarify the relation between PRS and FRB activities. Active repeaters with PRS may either be a distinct population or FRB sources at earlier evolutionary stages.
Figure 1: Top row: Frequency integrated burst intensities that were detected during FAST observations. These six bursts are chosen from each observation epoch by its characteristic dynamic spectra. The ’P0’ means the first burst of all the 79 bursts. Middle: De-dispersed dynamic spectra of the bursts clearly showing the band-limited nature of these bursts. The color are linear scaling and darker patches represent higher intensities. The bad frequency channels are set to zero and labeled in red patches on the left. The time and frequency resolutions for the plots are downsampled to 0.786 ms and 3.91 MHz, respectively. Bottom: The number of bursts detected at each epoch. The red lines span the observation windows of that day and the blue crosses represent the number of bursts detected in that observation.
Figure 2: Optical, infrared, and radio images of the field of FRB 190520B. In each case, the box is 40″ in size and the 2″ crosshairs indicate the best FRB position at 16h 02m 04.2683s −11°17′17.3203″ 16h02m04.266s, −11°17′17.33′′. (Left) An optical $R'$-band image obtained by CFHT MegaCam covers 5427Å–7041Å, including redshifted Hβ4861Å, [OIII]4959Å, and [OIII]5007Å emission lines from the host galaxy. (Middle) The infrared $J$-band image by Subaru/MOIRCS shows emission only at the location of the peak of the optical light profile of the host galaxy. (Right) The radio VLA image (2–4 GHz) shows a compact persistent source at the FRB location. The synthesized beam is shown as an ellipse of size (0.92′ × 0.47′) in the left corner.
Figure 3: Galactic and extragalactic contributions to the DM observed for FRBs with firm host galaxy associations and redshifts, adapted from ref. 1, 36. Sources localized on initial detection (“one-off” bursts) and repeating FRBs are identified separately. Galactic disk contributions are estimated from NE200117 with an additional halo contribution of $50 \pm 25$ pc cm$^{-3}$ (full range; this range is also reflected in the error bars plotted for the extragalactic DM). The expected DM contribution of the intergalactic medium (orange line) is $978$ pc cm$^{-3} f_{\text{IGM}} f(z)$, where $f(z) \approx 1.06z$ at $z \sim 0.24$ and the baryonic fraction in the ionized IGM is $f_{\text{IGM}} \sim 0.85$, with a $1\sigma$ band $\pm \sqrt{50 \times \text{DM}_{\text{IGM}}}$ pc cm$^{-3}$ due to cosmic variance. The host galaxy contributions $\text{DM}_{\text{host}}$ shift observed values to the right of the band of extragalactic DM predicted for the intergalactic medium alone. FRB 190520B is a clear outlier from the general trend, with an unprecedented DM contribution from its host galaxy. FRB 121102 is identified for comparison.
Table 1: Properties of FRB 190520B

| Source name       | FRB 190520B |
|-------------------|-------------|
| **Measured Parameters** |             |
| Right Ascension (J2000) | $16^h02^m04^s.266$ |
| Declination (J2000)    | $-11^\circ17'17''.33$ |
| Galactic Coordinates $(l,b)$ | $359^\circ.67, 29^\circ.91$ |
| Number of detections$^a$ | 81 |
| Dispersion Measure ( pc cm$^{-3}$) | $1210.3\pm0.8$ |
| Measured width (ms)   | $13.5\pm1.2$ |
| Scattering timescale (ms) at 1.25GHz | $9.8 \pm 2$ |
| Scintillation bandwidth (MHz) at 1.4GHz | $0.29 \pm 0.15$ |
| Measured fluence (Jy ms) | 0.03 to 0.33 |
| $DM_{MW}$ ( pc cm$^{-3}$)$^b$ | 60 , 50 |
| $DM_{host}$ ( pc cm$^{-3}$) | $902^{+88}_{-128}$ |
| Luminosity distance (Mpc) | 1218 |
| Isotropic energy (10$^{37}$ erg) | 3.6 to 40 |
| **Persistent Radio Source** |             |
| Right Ascension (J2000) | $16^h02^m04.259^s$ |
| Declination (J2000)    | $-11^\circ17'17.38''$ |
| Flux at 3.0 GHz ($\mu$Jy) | $202 \pm 8$ |
| **Host galaxy**       |             |
| redshift ($z$)        | $0.241 \pm 0.001$ |
| $M_\odot$ $^c$        | $\sim 6 \times 10^8$ |
| H$\alpha$ luminosity(10$^{40}$ erg sec$^{-1}$) | $7.4 \pm 0.2$ |
| SFR (yr$^{-1}$) $^d$ | $\sim 0.41 M_\odot$ |

$^a$ Including the FAST and VLA observations

$^b$ The MW electron density mode from NE2001 and YMW16.

$^c$ Based on the $J$-band magnitude

$^d$ Based on the H$\alpha$ luminosity.
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**Author contributions** CHN discovered the source FRB 190520B. DL, CL, SC, CWT, WY, CHN initiated the follow-up projects. DL, CHN, BZ, WWZ led the follow-up FAST observations. CHN, JMY, YKZ, PW, DJZ, YF searched and processed the FAST data. WY is the PI of the VLA observations and requested simultaneous FAST and Swift ToO observations. KA, CL, SC, XZ, SBS, ZY, WY, LC contributed to the VLA burst detection and localization, identification and measurements of the associated PRS. CWT, SC, DS, YN, JJ, CB, GDL contributed to the Optical/NIR follow-up observations, host galaxy photometry, morphology, and spectroscopic analysis. ZY and WY contributed to the Swift data analysis. SO, JMC, SC, JMY, CHN contributed to measured the burst scattering, modeling combined with analysis of propagation effects and DM-z analysis. JMC, BZ and WYW contributed to the DM_{host} estimation. KA, YKZ, JRN, RL, WWZ, CHN, contributed to the signal period and burst rate analysis. PW, YKZ helped on energy calibration and MY contributed to the RFI removal on FAST data. MC led the Effelsberg follow-up, SD led the Parkes observations, and YLY led the FAST-VLBI experiment. SBS, DL, KA, CHN, SC, JMC, and CL had major contributions to the preparation of the manuscript. All of the authors have reviewed, discussed, and commented on the present results and the manuscript.

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**Methods**

1 **Observations**

**FAST** CRAFTS is a multi-purpose drift scan survey conducted with FAST using a 19-beam receiver operating at 1.05–1.45 GHz, deployed in May 2018 and conducting blind FRB searches using multiple pipelines\textsuperscript{33}. FRB 190520B was discovered on November 16th 2019 in archived CRAFTS data which is in 1-bit filterbank format with 196 $\mu$s time resolution and 0.122 MHz frequency resolution. In this first discovery observation, 3 bursts were detected in 10 seconds, and another burst was detected 20 seconds later. These 4 bursts from the drift scan survey gave a preliminary location for the source within a $\sim$ 5 arcmin diameter region. Taking the pointing location from FAST, 2 follow-up observations were performed with FAST on April 25th and May 22nd in 2020 with 19-beam mode in which 15 bursts were detected. A monthly observation campaign was then conducted by FAST using the $\sim$ 100 mas localization from VLA (next section). After some regular telescope maintenance, 10 observations were performed spanning from July 30th 2020 to September 19th 2020 in which 60 more bursts were detected.

Bursts were detected from FRB 190520B in each FAST monitoring observation. We list the properties of those bursts detected by FAST in supplementary Table 1. The burst arrival time is in MJD format and has been transformed to the arrival time at the solar system barycentre (SSB) at 1.5 GHz with the DM values from supplementary Table 1. The observed DM$_{obs}$ is measured using the method from ref.\textsuperscript{25} and code from ref.\textsuperscript{34}. We use the DM value of the burst with the highest S/N for maximum DM structure(see result plot from ref.\textsuperscript{23}), and report the DM for all other bursts.
detected in that date.

The FAST observation data was searched using a Heimdall based pipeline\textsuperscript{[21,25]}. For the FRB blind search in 19-beams drift scan survey, the polarizations were merged and only kept Stokes I, the trial DM range is from 100 to 5000 pc cm\(^{-3}\) and we matched the pulse width by a boxcar search. The candidates above a S/N of 7 and present in less than 4 adjacent beams were manually examined for further inspection. After we identified FRB 190520B as a new FRB source, the follow-up burst search was taken with narrower DM range (100-2000 pc cm\(^{-3}\)). Following the VLA localization, the tracking observation only recorded data from the central beam but with all the Stokes parameters and higher time resolution (49.98\(\mu\)s). Candidates with S/N>7 sigma correspond to a fluence threshold of 9 mJy ms.

The pulse widths were estimated by a Gaussian profile fit if the burst showed no obvious sign of scattering. The sub pulse is recognized if the profile peak does not fall behind the noise baseline. If the burst shows a scattering tail (see Section\textsuperscript{[5]}), the pulse width is derived from the scatter tail fit. The bandwidth of each burst is roughly estimated by its spectrum after the radio frequency interference (RFI) elimination.

\textbf{VLA} Following the FAST detection of bursts from FRB 190520B and its high burst rate, VLA observations were performed from July-October 2020 at the most reliable position determined using FAST detections. At the time of proposing, the location of this FRB was constrained to within 5 arcmin using multiple burst detections at FAST. The observations were done under the approved DDT project: 20A-557 and were performed at L, S and C bands. In total, 11.4 hrs were
spent on the source. Most of the observations were in the B array configuration (with a maximum baseline of 11.1 km), with the exceptions that the array configuration was BnA on MJD 59161 and BnA->A on MJD 59167 and 59169.

The total bandwidths at L (1.5 GHz), S (3 GHz), and C (5.5 GHz) bands were 1024, 2022 and 2022 MHz, respectively, with 1024 channels, corresponding to channel band-widths of approximately 1, 2 and 2 MHz.

The details of the observations are given in Extended Data (ED) Table 1. The telescopes were pointed at the field centered at (RA, Dec)[J2000] = (16h02m01s, −11d17m28s). We note that due to a system error the realfast system wasn’t run on the VLA observation on MJD 59169. However, this observation was used to make a deep radio image at S band.

We used the realfast search system at VLA to search for bursts from FRB 190520B in our VLA observations. The realfast search system has been described in detail in Refs[10,36], but here we discuss it briefly. Using a commensal correlator mode, the visibilities are sampled with 10 ms resolution and distributed to the realfast GPU cluster for transient search. The search pipeline rfpipe then applies the online calibration, de-disperses the visibilities and forms images at varying temporal widths. The $8\sigma$ fluence limit of a 10 ms image is 0.4 Jy ms. Candidates with image S/N greater than the threshold triggered the recording of fast sampled visibilities around 2-5 seconds of the candidate. For each candidate, time-frequency data corresponding to the maximum pixel in the image is then extracted and post-processed. It is then classified by fetch, a GPU based convolutional neural network to classify radio transients from non-astrophysical signals[38].
Interesting candidates are then visually checked by the *realfast* team and marked for further offline analysis.

Promising candidates selected by the *realfast* team go through an offline analysis to refine the parameters of the candidate, and improve its detection significance, if possible. Several methods are tried within this analysis: offline search for the transient using a finer DM grid, varying RFI flagging thresholds, changing image size (as realtime-search is done on non-optimal image size due to computational limitations), sub-band search etc. (see Section 2.4 of ref. [36] for more details). The pixel sizes of images formed by realtime system at L, S and C band were: 0.9″, 0.48″ and 0.27″, with an image size of 2048×2048 pixels corresponding to fieldsize of: 0.5°, 0.27° and 0.15°. During refinement, we searched the data with smaller pixel sizes: 0.5″×0.75″ at L band, 0.38″×0.28″ at S band and 0.27″×0.18″ at C band. Significance of an astrophysical transient should improve when the data is de-dispersed at a DM closer to the DM of the candidate (see Section 2 of ref.[39]). Therefore, we re-ran the search with a finer DM grid at 0.1% fractional sensitivity loss, as compared to 5% used by the realtime system. Noise like events or RFI are sensitive to RFI flagging and image gridding parameters, and so they cannot be reproduced on refinement, and are discarded. Sometimes the transient signal is present only in a subband out of the whole bandwidth, so we also rerun our search only using the relevant frequencies, which further improves the detection significance. We applied all these techniques on all the interesting candidates from these observations, and used those refined parameters further in the analysis.
Localization of bursts

Calibration The images generated by the real-time system make several assumptions during calibration and imaging. This is to improve the computational efficiency and perform the imaging and search in real-time. Moreover, the Point Spread Function (PSF) of the interferometer is not deconvolved from the image, so the real-time system forms “dirty” images. The PSF shape makes the images more difficult to visually interpret and model.

To address these issues, we used the raw, de-dispersed, fast sampled visibilities with just the burst signal to re-image the burst data with Common Astronomy Software Application package (CASA v5.6.2-3). We first downloaded the VLA calibration pipeline tables corresponding to each observation with the burst. We then applied those calibration and flagging tables to the burst data using CASA task applycal. Observation of 3C 286 (before the FRB observation) was used to calibrate the flux density scale, bandpass and delays. Complex gain fluctuations over time were calibrated with observations of calibrator J1558−1409. We performed phase-reference switching on intervals of 16, 13, and 12 minutes for L, S, and C-bands, respectively; these are consistent with the suggested phase-coherence timescales for the VLA. This was to ensure that after calibration, any short-timescale phase variations would be negligible. Therefore, the burst positions on short timescales will have systematic errors of the same magnitude as the deep imaging. These systematic errors are discussed below in Section 3.

Determining properties of individual bursts After calibration, we used the CASA task tclean to generate the image and estimate an image Signal to Noise (S/N). For each burst, we search dif-
fferent spectral window ranges to generate the image with highest S/N. This is because most of the bursts are frequency modulated, and therefore selecting a sub-band would improve the detection significance. We then use the CASA task imfit around the rough FRB position to fit an ellipse to the source in the radio image and measure the centroid location, peak flux density and 1σ image-plane uncertainties. Hereafter, we refer to these image-plane uncertainties as statistical errors on burst positions.

We then take the weighted average of burst positions for each frequency band separately, by weighing each position by the inverse of the position fit errors (statistical errors) reported by CASA. This weighting scheme accounts for the effects of different beam size at different frequencies along with different significance of detection. This weighting scheme is used because statistical errors are inversely proportional to S/N, and therefore high significance detection is expected to have smaller fit errors. We then propagate this total statistical error for each frequency band, and add it in quadrature with the systematic error at that frequency (determined using the deep radio images described in Section 3), to obtain the total positional error at each frequency band. This total positional error (R.A. error, Decl. error) was: (0.16″, 0.22″) at L band, (0.13″, 0.14″) at S band and (0.23″, 0.22″) at C band. The error is dominated by systematic uncertainties at each frequency band (see ED Table 2 and ED Table 3). Finally, we take a weighted average of the three burst positions at the three frequency bands, weighing each position by the inverse of the total error obtained at the respective frequency band. Using this, we obtained the best estimate for burst position of: R.A. = 16h02m04.266s, Decl. = −11d17m17.33s (J2000). We estimate the error on this position to be 0.09″ and 0.10″.
We use burstfit to model the spectro-temporal properties of bursts. This analysis extends the discussion of ref.\textsuperscript{41} and has been described in ref.\textsuperscript{42}. We model the pulse profile and the spectra using a Gaussian function, and therefore fit for 6 parameters: mean of pulse, width of pulse, mean of spectra, width of spectra, fluence and DM. Following ref.\textsuperscript{42}, we use curve_fit followed by MCMC methods to estimate the posterior distribution of these fit parameters. The fitted properties of the VLA bursts are given in ED Table 4.

We now highlight some important caveats to this burst modeling. The time resolution of the VLA observations was 10 ms. This is comparable to (or more than) the widths of all the bursts detected using VLA. Due to this any temporal structure in the bursts (multiple components, scattering, sub-burst drift) would be resolved out and we would not be able to model it. Therefore, the widths estimated here should be considered as upper limits. We also could not estimate a structure maximizing DM for VLA bursts because of the large time resolution. The DMs reported here are the values that maximize the S/N. This also explains the apparent variability seen in the DM values. Burst S5 was very weak, and hence its fit estimates are not well constrained. Further, the bursts that extend beyond the observable bandwidth can also have unreliable estimate of fluence and spectral width. This is true for three bursts (L1, S1 and S5), and we have marked these bursts with a † in the table. Burst times are defined in barycentric MJD time that are referenced to the frequency at the top of the receiver band referenced in the burst name. For bursts in L, S, and C bands, the reference frequencies are 2032, 4012, and 6512 MHz, respectively.
3 Persistent Radio Source

Deep radio images and PRS  The VLA campaign obtained two epochs at 1.5 GHz and six epochs at 3 GHz and 5.5 GHz, which resulted in an on-source time of \( \sim 3 \) hours for 1.5 GHz, and \( \sim 4 \) hours for both 3 GHz and 5.5 GHz.

The VLA visibilities with 3 s or 5 s sampling time for the whole observation were saved and analyzed to search for persistent radio emission. This is done in parallel to saving the high time resolution (10 ms) data around the burst that was used in the previous section. We used standard data reduction, including flagging and calibration with the CASA software package. We used 3C 286 as the primary calibrator for flux scaling and bandpass calibration. J1558–1409 was used as secondary calibrator to calibrate the complex gains as a function of time. We then performed further flagging on the target and then subsequently imaged its Stokes I data using the CASA deconvolution algorithm tclean. To balance sensitivity while reducing sidelobes from a nearby bright source, we imaged with a Briggs weighing scheme (robust=0). In addition, self-calibrations were performed for all observations to correct considerable artefacts from the close-by bright sources in the field. We made use of the CASA task imfit to measure source flux densities by fitting an elliptical Gaussian model in the image plane.

We stacked observations at each central frequency in the uv-plane and then imaged the Stokes I intensity, resulting in 1.5 GHz, 3 GHz, and 5.5 GHz deep images with rms noise of 9.0, 4.5, and 3.0 \( \mu \text{Jy/beam} \), respectively. The obtained positions for the PRS are shown in ED Table 2. The systematic offsets on these positions are estimated in the next section.
Systematic Offsets In order to determine the systematic errors on the coordinates of the PRS that we determined from the deep images, we ran PyBDSF [https://www.astron.nl/citt/pybdsf/index.html] package to extract radio sources from the deep images. We then cross-matched the detected point sources in the deep images with the sources listed in the optical PanSTARRS survey DR1 [43]. We identified the radio point sources using the following criteria:

- The peak intensity (Jy/beam) of a source should be 0.7, 0.5, 0.5 times higher than its integrated flux (Jy) for the 1.5 GHz, 3 GHz and 5.5 GHz images, respectively.

- The S/N (peak intensity / local rms noise) of a source should be greater than 5.

In total, we detected 375, 113, and 43 sources in the 1.5 GHz, 3 GHz and 5.5 GHz deep image, respectively. We visually checked the selected sources to make sure that they are ‘point-like’ sources in the deep images. Of those, 109, 27, and 9 sources had an optical source within 0.5 arcsec in the PanSTARRS DR1 catalogue. By comparing the offsets of these cross-matched sources, we estimate the systematic offsets in our 1.5 GHz, 3 GHz and 5.5 GHz positions. They are listed in ED Table 2. The errors on the systematic offsets are consistent with zero and the uncertainty in that offset dominates the uncertainties of the position of the PRS. We consider the uncertainties on these offsets as the systematic errors on the positions determined at each frequency band.

Determining position of the PRS To determine the position of the PRS from the detections at three frequency bands, we followed a procedure similar to what was used to determine the burst positions (see Section 2). For each frequency band, we estimated the total positional error by
adding the systematic and statistical error (listed in ED Table 2) on the positions in quadrature. We then take a weighted average of PRS positions at the three frequency bands, by weighing each position by the inverse of the total positional error. Using this, we obtained the best estimate for PRS position of: R.A. = 16h02m04.259s, Decl. = −11d17m17.38s. We estimate the error on this position to be 0.09″ and 0.10″.

**Variability and Spectrum of the PRS** The flux density of the source measured in each epoch is shown in ED Table 1. Measured flux densities show no evidence for refractive interstellar scintillation, with variations in flux densities consistent with measurement errors. This can be accounted for if the source is more extended than the PRS for FRB 121102.

In order to study the spectrum of the PRS, we split each of the observations into two, 1 GHz sub-bands. Then we measured the average flux density at each of the sub-bands over the campaign. By applying a Power-Law (PL) model to fit the multi-band data, we determined the average PL spectral index of the PRS as −0.41±0.04. This is shown in ED Figure 2.

**Chance of coincident association of the PRS** In the 1.5 GHz deep image, we detected 8 ‘point-like’ sources, including the PRS (based on our point-source selection criteria described earlier), with a flux density higher than 260 µJy within 5 arcminutes of the phase center. There is an additional bright source with a flux density of a few tens mJy in the region, but it was not classified as a ‘point-like’ source based on our criteria.

To estimate the chance coincidence probability of the PRS with the bursts, we compared the solid angle corresponding to the uncertainty of burst localization and the average solid angle
occupied by each of the eight ‘point-like’ sources in the FRB field-of-view. The solid angle corresponding to each of the 8 ‘point-like’ sources is roughly estimated as $S_{\text{source}} = \pi (5/60)^2 / 8 \text{ Sr}$. The offset between the average position of the nine bursts and the position of the PRS at 3 GHz, which is best constrained when taking both statistical and systematic errors into account, is about 0.13 arcseconds. This, along with a statistical error of 0.02 arcseconds and a conservative estimate of the systematic error of 0.15 arcseconds, can be used to estimate the offset between the PRS and the FRB position. We conservatively estimate this offset to be 0.3 arcseconds. The solid angle corresponding to the offset therefore can be estimated as $S_{\text{offset}} = \pi \times (0.3/60/60)^2 \text{ Sr}$. The ratio between $S_{\text{offset}}$ and $S_{\text{source}}$ gives the chance of coincident association of the PRS with the FRB position to be $\approx 8 \times 10^{-6}$.

4 Galaxy Photometry and Redshift Determination

The deep $R'$-band (5427Å- 7041Å) images obtained by CFHT/MegaCam are stacked from archival observation data taken in 2014-2015 by the CFHT archival pipeline MEGAPIPE, with a total $\sim 3.6$ hours on the field. The level 3 (flux calibrated) images are retrieved for our analysis.

NIR $J$-band images of the FRB 190520B field were taken under a relatively poor seeing condition ($\sim 1.3''$) through the Subaru ToO observation on August 5th 2020. A total of 1.4-hour observations were used for the final combined $J$-band image shown in Figure 2. A $J$-band blob of 22.07±0.14 mag (AB) was detected at $\sim 1''$ south east of the burst location, possibly the stellar emission of the host galaxy. A faint northern blob at 2.5'' north has 22.87±0.26 mag in $J$-band. None of these two sources are detected in $K_s$-band image, with a 5-sigma limit of 21.74 mag (1.1
An optical spectrum was obtained with Double Spectrograph (DBSP) on the Palomar 200-inch telescope on 24th July 2020 using a 1″ slit-width. This observation was executed before the CFHT archival MegaCAM data on FRB 190520B field were found, and only Pan-STARRS images were used for observation planning. The slit of DBSP was set to cover the persistent radio source emission at RA = 16:02:04.27; Dec. = −11:17:17.5 detected by VLA in L-band on 22nd July 2020. The PRS location later is found to coincide with the location of the burst emission from FRB 190520 within 0.12″. No clear optical counterpart was detected in any of the 5 band images of PanSTARRS from DR1. The slit was guided by the nearby M-star at RA = 16:02:04.48, Dec. = −11:17:19.1 as reported in PanSTARRS DR1 catalog, with $i = 20.4$ mag, and due east of 3.4″ away from the coordinate of the VLA PRS. The slit was set to a position angle of 108.5 degrees, allowing both the coordinate of VLA persistent radio source and the M-star to fall into the slit. The observations with 2×900 s exposures were carried out under photometric sky condition and sub-arcsecond seeing. The 2D spectrum was generated in IRAF, including bias removal, flat-fielding, and reduction of other instrumental effects. The 1D spectrum was extracted from a 1.5″ window. The standard star BD+28 4211 is used for telluric correction and flux calibration. The DBSP 1-D spectrum is shown in Figure 3. The flux scale of the spectrum does not include the slit loss and registration error of Pan-STARRS coordinates of the M-type star. The [OIII] 5007Å line and the Hα line are both well detected (> 5σ). Two emission lines are narrow, with a FWHM of ∼10Å. The corresponding redshift derived based on these two spectral lines is $z = 0.241 ±0.001$.

A follow-up Keck LRIS spectroscopic observation was carried out on 25th August 2020
under reasonable weather and seeing conditions (1.1′′). The 1.5′′ slit was set at a position angle of 160° to the extended optical emission seen in the MegaCam $R'$-band image around the FRB 190520B location. A total exposure of 3600 s was obtained. The emission lines H$\alpha$, H-\$\beta$, [OIII]4859Å, and [OIII]5007Å are well detected, indicating the extended $R'$-band structure has the same redshift of $z = 0.241$.

**Chance association probability of host galaxy** We use the approach of\(^{11}\) to estimate the chance coincidence probability of the galaxy (J160204.31−111718.5) to that of the burst. They assume a uniform surface distribution of galaxies and therefore the probability of chance coincidence follows a Poisson distribution i.e $P = 1 - \exp(-n_i)$, where $n_i$ is the number density of galaxies brighter than a specified $R'$-band magnitude, in a circle of given radius, determined by the half light radius of galaxy and the localization error region. This number density is estimated using the results from\(^{11}\). From Section 2 and Section 3 we assume the localization error on the FRB location to be $\sim 0.1$, the size of the host galaxy to be 0′.5. The $R'$-band magnitude of the possible host is difficult to estimate since it is significantly affected by the emission lines. Thus we conservatively estimate the $R'$-band magnitude to be $\lesssim 23.3$ mag assuming a flat SED in $\nu L_{\nu}$ between $R'$-band and $J$-band. These yield a probability of FRB association to an unrelated galaxy to be $\sim 0.8\%$.

5 FAST Burst Sample Analysis

**Repetition rate** FRB 190520B is very active and bursts from it were detected in each monitoring observation with FAST. Because of the possible clustering behavior of FRB emission, a Weibull
is used to describe the distribution of waiting time\textsuperscript{75}, where \( k \) is the shape parameter, \( \lambda \) is the scale parameter of the distribution and \( \delta \) is the waiting time. The mean of a Weibull distribution can be expressed as \( E(\delta) = \lambda \Gamma(1 + 1/k) \), the reciprocal of the mean is \( r = 1/E(\delta) \), which indicates the burst rate of the FRB emission. The Weibull distribution reduces to the Poissonian case when \( k = 1 \), ED Figure 4 shows the result of the parameters distribution obtained with Markov Chain Monte Carlo (MCMC). We find the burst rate of FRB 190520B is \( r = 4.5^{+1.9}_{-1.5} \) hr\(^{-1} \) with shape parameters \( k = 0.37^{+0.04}_{-0.04} \) for all 79 bursts which are above > 7σ (left panel in ED Figure 4), and \( r = 5.3^{+1.1}_{-1.0} \) hr\(^{-1} \) with shape parameters \( k = 0.76^{+0.09}_{-0.08} \) when excluding waiting times shorter than 1 s (right panel in ED Figure 4).

**Short and long time scale periodicity search** For a range of trial periods \( (P) \) and period derivatives \( (P) \), the ToAs of the 79 bursts were folded to acquire the phase of each burst in the period phase space. The longest contiguous phase segment without bursts was calculated in each fold trial. A high value means that the burst is concentrated in a small phase window, which indicates a possible periodicity pattern.

For the short time scale periodicity, the bursts are aligned according to the arrival time of the first burst in each observing session, we then folded the ToAs at \( P \) between 1 ms and 1000 s and \( \dot{P} \) between \( 10^{-12} \) and 1 s. The longest contiguous inactive phase fraction is smaller than 0.4 in ED Figure 5 left panel, in other words, the bursts spread to a phase window larger than 60% of one period, which indicates no periodicity pattern in the trial range.
For the long time scale periodicity, the trial range of $P$ is from 2 to 365 d and $\dot{P}$ from $10^{-12}$ to 1 d. The continuous inactive phase fraction shows two maxima about 0.6 near 67 d and 169 d in ED Figure 5 middle panel. These two maxima can be reproduced by folding the MJDs of all observation session in ED Figure 5 right panel, which indicates the observation selection effects rather than true periodicity patterns. Thus, no long or short period of FRB 190520B was detected.

**Energy distribution** A 1-Kelvin equivalent noise calibration signal was injected before each observation session to obtain high quality flux density and energy calibration measurement for each detected burst. The injected noise calibration signal was used to scale the data noise level of the baseline to the system temperature ($T_{\text{sys}}$) units, the standard deviation of off-pulse brightness is nearly constant within 6% for all observations. The variation in the off-pulsed noise level mainly comes from the zenith angle depended telescope gain. The Kelvin unit was then converted to Jy using the zenith angle-dependent gain curve, provided by the observatory through quasar measurements\(^4\). For most observations, the zenith angle $< 20$ degrees, which corresponds to a stable gain of $\sim 16$ K/Jy. The zenith angle-dependent gains were then applied for the amount of pulsed flux above the baseline, giving the peak flux measurement of the detected bursts.

Assuming it is of flat broadband spectrum, We then calculated the isotropic equivalent burst energy, $E$, following Equation (9) of ref.\(^1\):

$$E = (10^{39}\text{erg}) \frac{4\pi}{1 + z} \left( \frac{D_L}{10^{28}\text{cm}} \right)^2 \left( \frac{F_\nu}{\text{Jy} \cdot \text{ms}} \right) \left( \frac{\nu}{\text{GHz}} \right),$$

(2)

where $F_\nu = S_\nu \times W_{eq}$ is the specific fluence in units of erg cm$^{-2}$Hz$^{-1}$ or Jy \cdot ms, $S_\nu$ is the peak flux density which has been calibrated with the noise level of the baseline, giving the flux measurement.
for each pulses at a central frequency of $\nu_c = 1.25$ GHz, $W_{eq}$ is the equivalent burst duration, and the luminosity distance $D_L = 1218$ Mpc corresponds to a redshift $z = 0.241$ for the source of FRB 190520B.

The fluence-width distribution at 1.25 GHz for FRB 190520B bursts can be seen in ED Figure 6. The histogram of burst energies (ED Figure 7) exhibits a clearly bump, which can be well fit by a log-normal function.

**DM analysis** The total of 79 bursts detected in 16 months show a faint trend in DM. ED Figure 8 shows the estimated DM values with respect to time. The DMs of each day use the best-fit DM value of that day. The $\Delta$DM are $-0.09 \pm 0.02$ pc cm$^{-3}$ $d^{-1}$. More detection are needed for a detailed analysis.

The observed DM can be separated into four primary components:

$$DM_{obs} = DM_{MW} + DM_{halo} + DM_{IGM} + DM_{host}$$

where $DM_{MW}$ is the contribution from the Milky Way’s interstellar medium, $DM_{halo}$ is the contribution from the Milky Way halo, $DM_{host}$ the contribution from the host galaxy including its halo and any gas local to the FRB source, and $DM_{IGM}$ is the contribution from the intergalactic medium.

We use the NE2001 model to evaluate $DM_{MW} = 60$ pc cm$^{-3}$ (compared to 50 pc cm$^{-3}$ from the YMW16 model), which we use as the mean of a flat distribution with 40% width to conservatively represent the uncertainty in $DM_{MW}$ at the Galactic latitude of FRB 190520B. For the MW halo contribution, we use a flat distribution from 25 to 80 pc cm$^{-3}$. Together the MW disk
and halo components yield a total mean of 113 pc cm$^{-3}$ and RMS uncertainty of 17 pc cm$^{-3}$.

For the IGM we use the ΛCDM cosmological model to calculate the mean DM contribution$^{19}$,

$$\text{DM}_{\text{IGM}}(z) = \frac{3cH_0\Omega_b f_{\text{IGM}}}{8\pi Gm_p} \int_0^z \frac{\chi(z)(1+z)dz}{[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}}, \quad (4)$$

where the free electron number per baryon in the universe is $\chi(z) \approx 7/8$, (assumed constant for FRB redshifts), the normalized matter density is $\Omega_m = 0.315 \pm 0.007$, the dark energy fraction is $\Omega_\Lambda \simeq 1 - \Omega_m$, the baryonic fraction is $\Omega_b = h^{-2} \times (0.02237 \pm 0.00015)$, and the Hubble constant is $H_0 \equiv h \times 100$ km s$^{-1}$ = 67.36 ± 0.54 km s$^{-1}$Mpc$^{-1}$.$^{20}$ Using values for the speed of light $c$, the gravitation constant $G$, and the proton mass $m_p$, the resulting expression,

$$\text{DM}_{\text{IGM}}(z) \approx 978 \text{ pc cm}^{-3} f_{\text{IGM}} \int_0^\infty \frac{(1+z)dz}{[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}}, \quad (5)$$

yields $\text{DM}_{\text{IGM}}(0.241) = 248 f_{\text{IGM}} \text{ pc cm}^{-3}$, where $f_{\text{IGM}}$ is fraction of baryons in the ionized IGM.

Using $\text{DM}_{\text{IGM}}(z)$ as the mean, we calculate the error using a log-normal distribution that yields

$$\sigma_{\text{DM}_{\text{IGM}}}(z) = [\text{DM}_{\text{IGM}}(z)\text{DM}_c]^{1/2},$$

where $\text{DM}_c = 50 \text{ pc cm}^{-3}$ is chosen to provide an uncertainty consistent with published simulations. This gives $\sigma_{\text{DM}_{\text{IGM}}}(0.241) = 111 f_{\text{IGM}} \text{ pc cm}^{-3}$.

To constrain the host-galaxy DM, we combine the MW and IGM estimates and their uncertainties with the measured DM averaged over all bursts, which is $\text{DM}_{\text{obs}} = 1210.3 \pm 0.8 \text{ pc cm}^{-3}$, the uncertainty is due to the measurement. Using $f_{\text{IGM}} = 0.85$ for the baryon fraction in the IGM$^{18}$, we obtain a median value for $\text{DM}_{\text{host}}$ and 68% probable interval $\text{DM}_{\text{host}} = 902^{+88}_{-128} \text{ pc cm}^{-3}$. Corresponding to this is $\text{DM}_{\text{IGM}} = 195^{+110}_{-70} \text{ pc cm}^{-3}$ for the IGM contribution.

For comparison we give redshift estimates for different values of $f_{\text{IGM}}$ if a fixed value of $\text{DM}_{\text{host}} = 50 \text{ pc cm}^{-3}$ is used (as is often found in the literature) along with the above quoted mean
value for the MW contribution. For $f_{\text{IGM}}$ ranging from 0.6 to 1, we obtain mean redshift values of 1.61 to 0.96, respectively, much larger than for the identified host galaxy.

The DM of the host galaxy is independently estimated from its Hα emission by converting the extinction-corrected Hα flux, $F_{\text{H}\alpha} = (9.4 \pm 0.3) \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, to an Hα surface density of 503 ± 14 Rayleighs in the source frame at $z = 0.241$, assuming host galaxy dimensions of 0.5 by 0.5 arcseconds$^5$. These host galaxy dimensions are only a rough estimate based on the size of the Hα emitting region in the Keck image, but because the image is seeing limited the assumed dimensions may be even smaller, which would only serve to increase the Hα surface density in the following calculations. The Hα surface density $S(\text{H}\alpha)$ is related to the emission measure (EM) in the source frame by

$$\text{EM}_s = 2.75 \text{ pc cm}^{-6} (1 + z)^4 T_4^{0.9} S(\text{H}\alpha) \approx 1383 \pm 17 \text{ pc cm}^{-6} \times T_4^{0.9} \frac{S(\text{H}\alpha)}{503 \pm 14 \text{ R}},$$

where we have used the redshift $z = 0.241$ and $T_4$ is the temperature in units of $10^4$ K. The EM is related to the DM in the ionized cloudlet model$^5$ by $\text{EM} = [\zeta(1+\epsilon^2)/f]DM^2/L$, where $\zeta$ represents cloud-cloud variations in the mean density, $\epsilon^2$ represents the variance of density fluctuations in a cloud, $f$ is the filling factor, and $L$ is the path length through the gas sampled by the FRB. Using this relation, we obtain the corresponding source frame DM,

$$\text{DM}_s \approx 588 \pm 8 \text{ pc cm}^{-3} \times T_4^{0.45} \left[ \frac{L}{5 \text{ kpc}} \right]^{1/2} \left[ \frac{f/0.1}{\zeta(1+\epsilon^2)/2} \right]^{1/2} \left[ \frac{S(\text{H}\alpha)}{212 \pm 6 \text{ R}} \right]^{1/2},$$

where we have adopted fiducial values of $f = 0.1$ and $\zeta = \epsilon^2 = 1$, which are typical for the warm ionized medium in the Milky Way. For the path length through the gas we adopt a fiducial value of $L = 5$ kpc, which is based on the apparent size of the Hα emitting region in the host
galaxy. However, given that the optical image is seeing limited, and that the orientation of the galaxy relative to the FRB line-of-sight is not known, this path length could be as large as 10 kpc or as small as 0.1 kpc. For a range of $L$ from 0.1 to 10 kpc, we find that $DM_s$ could be as small as 260 pc cm$^{-3}$ or as large as 830 pc cm$^{-3}$, for the same fiducial values of $T_4$, $f$, $\zeta$, and $\epsilon^2$. The estimated DM is also highly sensitive to the temperature: for a range of $T_4$ from 0.5 to 5, $DM_s$ could range from 346 to 1212 pc cm$^{-3}$, keeping all other parameters fixed at their fiducial values. In the observer’s frame, the measured DM contribution of the host galaxy is smaller by a factor of $1/(1+z)$, yielding a nominal value of $DM_{host,coeff} \sim 474 \pm 7$ pc cm$^{-3}$ for the coefficient in Equation 7. The quoted errors only account for measurement errors in the H$\alpha$ flux. To match the inferred value of $DM_{host} \sim 900$ pc cm$^{-3}$ requires that the three factors in Equation 7 involving $T_4$, $L$ and $f$ combine to a factor $\sim 2$, which may easily be explained by a higher temperature or the broad range of possible values for $L$. Regardless, the large H$\alpha$ EM affirms that the FRB DM receives a significant contribution from ionized gas in the host galaxy, but it is unclear whether the diffuse, H$\alpha$ emitting gas can account for the entire host galaxy contribution or whether the FRB’s local environment contains significant ionized gas content that is not seen in H$\alpha$.

Galactic scintillation and extragalactic scattering Most of the pulses of FRB 190520B show scintillation-induced variation of intensity with frequency, which is quantified by the decorrelation bandwidth, $\Delta \nu_d$, defined as the half-width at the half maximum of the 1D autocorrelation function (ACF) of the spectrum for each burst:

$$ACF(\Delta \nu) = \frac{m}{\Delta \nu^2_d + \Delta \nu^2} + c,$$  

(8)
where $\Delta \nu$ is the frequency lag and $m$ and $c$ are free parameters. To measure the scintillation bandwidth, we selected 46 bursts with prominent scintillation effect and did 1D ACF for each burst. Then, we estimated the corresponding $\Delta \nu_d$ for each burst by fitting ED Equation to their ACF, and showed some of the results in ED Figure 9. Averaged scintillation bandwidth over 46 bursts we get $\Delta \nu_d$ is $0.29 \pm 0.15$ MHz at 1.4 GHz.

To demonstrate consistency with Galactic scintillation, we use DM = 60 pc cm$^{-3}$ from NE2001 and DM=50 pc cm$^{-3}$ from YMW16 along with an empirical scaling law for the Galactic scattering time, $\tau_d$, based on Galactic pulsars. Including the empirical spread in $\tau_d$ and a geometric correction that increases $\tau_d$ for an extragalactic source by a factor of three, we estimate the scintillation bandwidth, $\Delta \nu_d = 0.35^{+1.7}_{-0.29}$ MHz using the NE2001 DM value and $\Delta \nu_d = 0.46^{+2.2}_{-0.4}$ MHz for the YMW16 value at 1.4 GHz. These are in good agreement with the average observed value for the scintillation bandwidth, $\Delta \nu_d = 0.29 \pm 0.15$ MHz at 1.4 GHz.

Among the detected 79 pulses of FRB 190520B, 28 pulses show frequency-dependent temporal asymmetry that is consistent with scattering. To measure the pulse width and scattering timescale of FRB 190520B, we first integrate the dynamic spectrum along the frequency axis and normalize the resulting pulse profile. We fit pulses with scattering asymmetries using a Gaussian component convolved with a one-sided exponential component to fit the pulse profile, and use a single Gaussian component to fit the rest. The averaged scatter timescale and pulse width are $9.8 \pm 2.0$ ms and $13.5 \pm 1.2$ ms, respectively.

Examples of bursts with and without evidence of pulse broadening are shown in ED Figure.
Figure 11 shows the scattering timescale with respect to time.

The observed mean scattering time of 9.8 ± 2 ms at 1.25 GHz is far too small for the FRB’s host galaxy to lie behind our proposed host galaxy association. In this alternative scenario, the host galaxy would lie at a redshift $z_h > 0.241$ that depends on the foreground galaxy’s contribution to the total DM budget. The redshift implied by the DM-z relation with a foreground galaxy DM contribution of about 474 pc cm$^{-3}$ based on H$\alpha$ EM. The FRB would pass through the intervening galaxy at a redshift $z_l = 0.241$ at an impact parameter of about 4 kpc (based on the observed offset of the FRB localization in the optical images). The scattering contribution of the intervening galaxy lens is related to its DM contribution by:

$$\tau(DM, \nu, z) \approx 48.03 \, \mu s \times \frac{\tilde{F} G DM_l^2}{(1 + z_l)^3 \nu^4},$$

where $DM_l$ is the DM contribution of the lens galaxy in pc cm$^{-3}$ in the lens frame, $\nu$ is the observing frequency in GHz, $z_l$ is the lens galaxy redshift, and $\tilde{F} = \zeta \epsilon^2 / f(l_o^2 l_i)^{1/3}$ quantifies the electron density fluctuations in the lens for $\tilde{F}$ in units of pc$^{-2/3}$ km$^{-1/3}$, where $\zeta$, $\epsilon^2$, and $f$ describe the density fluctuation statistics and filling factor, $l_o$ is the outer scale of turbulence and $l_i$ is the inner scale. The geometric factor $G$ is unity for scattering in a host galaxy but it can be very large for an intervening galaxy, in which case $G \approx d_{sl} d_{lo} / d_{so} L$, where $d_{sl}$, $d_{lo}$, and $d_{so}$ are the angular diameter distances between the source and lens, lens and observer, and source and observer, respectively, and $L$ is the path length through the lens. For the smallest DM contribution implied by the H$\alpha$ emission, $DM_l \approx 260$ pc cm$^{-3}$, and a small path length through the intervening galaxy, $L \approx 1$ kpc, the implied scattering time is $\tau \approx 32$ s at 1.25 GHz. For the same DM contribution and a much larger path length $L \approx 50$ kpc, the scattering time would still be $\tau \approx 640$ ms, significantly larger
than the observed mean scattering time. Regardless of the intervening galaxy DM contribution, the leverage to scattering from $G$ is so large that the observed scattering time cannot be explained by an intervening galaxy, unless the path length through the gas responsible for the scattering is unrealistically large ($L \gtrsim 1$ Mpc). Such a large path length would imply some scattering from the intervening galaxy halo, but it has been shown that galaxy halos contribute negligibly to FRB scattering\textsuperscript{52}.

**Rotation measure** Rotation measure (RM) is searched at L-band with FAST data. The polarization was calibrated by correcting for differential gains and phases between the receptors through separate measurements of a noise diode injected at an angle of 45° from the linear receptors. We searched for the rotation measure (RM) from $-3.0 \times 10^5$ to $3.0 \times 10^5$ rad m$^{-2}$. No significant peak was found in the Faraday spectrum.

The observed polarization could be due to an intrinsic low linear polarization. Another possibility for the non-detection of RM is depolarization caused by intra-channel Faraday rotation. We estimate the depolarization fraction $f_{\text{depol}}$ caused by intra-channel Faraday rotation using Equation\textsuperscript{10}

$$f_{\text{depol}} = 1 - \frac{\sin(2\Delta \theta)}{2\Delta \theta},$$  \hspace{1cm} (10)

where the intra-channel Faraday rotation $\Delta \theta$ is given by

$$\Delta \theta = \frac{\text{RM} c^2 \Delta \nu}{\nu_c^3},$$  \hspace{1cm} (11)

where $c$ is the speed of light, $\Delta \nu$ is the channel width, and $\nu_c$ is the central channel observing frequency. Taking $\Delta \theta = 1$ rad, $\Delta \nu = 0.122$ MHz, and $\nu_c = 1.25$ GHz for our data, we get $\text{RM} =$
$1.8 \times 10^5 \text{ rad m}^{-2}$ and depolarization fraction of 54.5% caused by intra-channel Faraday rotation. Assuming that the pulse is 100% linearly polarized intrinsically and the non-detection of RM is caused by intra-channel Faraday rotation, we place an lower limit on the RM of $1.8 \times 10^5 \text{ rad m}^{-2}$. Such a large RM is even larger than that of FRB 121102 [67], which suggests that FRB 190520B also resides in an extreme magneto-ionic environment.
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Extended Data

Figure 1: Positions of the bursts and persistent radio source identified with VLA observations at 1.5, 3, and 5.5 GHz, shown as offsets from the best-fit position of the ensemble of bursts, at 16h02m04.266s, $-11^\circ 17' 17.33''$ (J2000). The uncertainties on the positions of the bursts are indicated with shaded ellipses, and those for the PRS are shown with error bars. These uncertainties include 1$\sigma$ statistical errors and estimates for systematic errors added in quadrature.
Extended Data | Figure 2: Spectral measurements of the PRS associated with FRB 190520B. The bandwidth is split into two sub-bands for all the observations and the corresponding radio flux densities are shown. The frequencies for each sub-band are shifted slightly in order to show the flux density error bars. The inset plot shows the average flux at each sub-band. By fitting a power-law model to these measurements, which is shown by the black dashed line, we derived the spectral index of the PRS as $-0.41 \pm 0.04$. 
Extended Data  |  Figure 3: Palomar DBSP optical spectrum of the FRB 190520B host galaxy. The redshift of $z = 0.241$ was determined with well-detected [OIII]-5007Å line and Hα line ($>5\sigma$). Two emission lines are narrow, with FWHM $\sim 10$ Å. The flux scale of the spectrum is not corrected for the slit loss.
Extended Data | Figure 4: Posterior probability distribution for shape parameters $k$ and event rate $r$ of the Weibull distribution. Left panel: fit to all waiting times of FRB 190520B from FAST. Right panel: fit to the waiting times longer than 1 s.

Extended Data | Figure 5: Periodogram obtained by folding the ToAs into the period phase space. The color indicates the longest contiguous inactive phase fraction and P1 stands for $\dot{P}$. Left panel is the folding results of all 79 ToAs with short trial periods (1 ms to 1000 s); middle panel is for all 79 ToAs with long trial periods (2 d to 365 d); right panel is the folding results for the MJDs of all observation session.
Extended Data | Figure 6: The fluence-width distribution at 1.25 GHz for FRB 190520B bursts. All the width and fluence values for 79 bursts of FRB 190520B are from supplementary Table 1.
Extended Data | Figure 7: The histogram of burst energies for FRB 190520B. The red line and black dashed line are the log-normal fit and 90% completeness threshold, respectively. The 90% completeness threshold uses 0.023 Jy ms which is the simulation result from ref.30.
Extended Data  |  Figure 8: The DM variation for FRB 190520B. FAST detected bursts span from 2019 May to 2020 August. We used the best-fit DM value of each observation epoch and show the linear fit to these DMs across all observations. The average DM value is shown in green dashed line.
Extended Data | Figure 9: The measured ACF for FRB 190520B. We show the autocorrelation function (ACF) for burst P5, P46, P42, P51 that for examples. The red line is the ACF, and the blue line is the best fit result. The averaged scintillation bandwidth at 1.4 GHz for FRB 190520B is $0.29 \pm 0.15$ MHz.
Extended Data | Figure 10: Dynamic spectra of bursts with and without scattering. The top row shows frequency-time dynamic spectra of bursts with significant evidence of pulse broadening, along with 1D burst profiles that have been averaged across the entire frequency band. The bottom row shows examples of bursts without significant evidence of pulse broadening. White lines indicate excised radio frequency interference. All 1D burst profiles have been normalized to a noise threshold of one. For P31, there is a potential combination of scattering, frequency drift, and multiple unresolved burst components; in this case we report a scattering time that should be interpreted as an upper limit. Bursts with scattering time constraints are shown in supplementary Table 1.
Extended Data | Figure 11: Scattering timescale with respect to observation time (MJD). The data are from the 28 bursts that showed scattering. Red line is a linear fit of all the bursts data which gives a variation of $2.4 \pm 6.8\text{ ms y}^{-1}$. Green dashed line represents the average scattering timescale of $9.8\pm 2\text{ ms}$ at $1.25\text{ GHz}$. 
### Extended Data

**Table 1:** Details of our VLA observations of the PRS and the number of bursts detected in each observation. Frequency is the center of the respective observing band and duration represents the total length of on-source observations. Note that the *realfast* system wasn’t run on the last observation due to a system error.

| Start Time (MJD) | Frequency (GHz) | Duration (min) | Beam size (”,”) | Flux density (µJy) | Bursts |
|------------------|-----------------|----------------|------------------|-------------------|--------|
| 59051.033815     | 1.5             | 96             | 4.78×2.90       | 258±16            | 1      |
| 59053.046790     | 1.5             | 96             | 4.63×2.90       | 273±23            | 2      |
| 59079.004955     | 5.5             | 41             | 1.38×1.02       | 145±10            | 0      |
| 59079.971533     | 5.5             | 41             | 1.44×1.05       | 164±11            | 0      |
| 59090.941498     | 5.5             | 41             | 1.45×1.04       | 158±9             | 0      |
| 59091.938768     | 3               | 41             | 2.43×1.85       | 195±14            | 5      |
| 59104.867225     | 3               | 41             | 2.76×1.76       | 160±13            | 0      |
| 59104.908789     | 5.5             | 41             | 1.43×1.04       | 151±9             | 0      |
| 59105.976837     | 3               | 41             | 2.44×1.60       | 186±15            | 0      |
| 59107.915546     | 5.5             | 41             | 1.38×1.02       | 153±10            | 1      |
| 59111.116215     | 3               | 41             | 5.00×1.45       | 176±16            | 0      |
| 59161.677240     | 5.5             | 41             | 1.92×0.47       | 139±13            | 0      |
| 59167.637761     | 3               | 41             | 2.76×0.51       | 233±17            | 0      |
| 59169.640486     | 3               | 41             | 2.47×0.48       | 211±14            | -      |
Extended Data | Table 2: Localised positions of the PRS from 1.5, 3, 5.5 GHz VLA deep images. The first column shows the observing central frequency. The second and third columns report the coordinates of the PRS from the deep images. The remaining columns show the 1σ statistical errors and the cross-matched systematic offsets in RA. and Dec..

| Frequency (GHz) | RA ("h m s") | Dec ("d m s") | Statistical Error RA (") |系统 Error Dec (") | Systematic Error RA (") | Systematic Error Dec (") |
|----------------|---------------|---------------|---------------------------|--------------------|--------------------------|--------------------------|
| 1.5            | 16h02m04.2543s | −11d17m17.4146s | 0.0386                     | 0.0713             | 0.0137±0.1539             | −0.0201±0.1981           |
| 3              | 16h02m04.2611s | −11d17m17.3869s | 0.0176                     | 0.0168             | −0.0187±0.1232            | 0.0232±0.1249            |
| 5.5            | 16h02m04.2618s | −11d17m17.3375s | 0.0075                     | 0.0095             | −0.0947±0.2263            | 0.1069±0.2090            |

Extended Data | Table 3: Localised positions of the VLA bursts. The label in the first column shows the frequency band of observation, followed by the burst number. DM represents the S/N maximizing DM obtained using offline refinement of the bursts and S/N reports the maximum image S/N. The remaining columns show the burst positions (and errors) obtained using CASA calibration and image fitting. The systematic errors reported here were estimated using deep radio images generated using all the observations at the respective frequency band.

| Band | S/N     | DM (pc cm⁻³) | RA ("h m s") | Dec ("d m s") | Statistical Error RA (") | Systematic Error Dec (") | Systematic Error RA (") | Systematic Error Dec (") |
|------|---------|--------------|---------------|---------------|---------------------------|--------------------------|--------------------------|--------------------------|
| L1   | 15.45   | 1209.60      | 16h02m04.2742s | −11d17m17.0535s | 0.124                     | 0.208                    | 0.1539                    | 0.1981                    |
| L2   | 26.68   | 1227.15      | 16h02m04.2847s | −11d17m17.1912s | 0.060                     | 0.145                    | 0.1539                    | 0.1981                    |
| L3   | 15.26   | 1236.60      | 16h02m04.2691s | −11d17m17.1299s | 0.070                     | 0.139                    | 0.1539                    | 0.1981                    |
| S1   | 18.93   | 1291.30      | 16h02m04.2567s | −11d17m17.4093s | 0.044                     | 0.080                    | 0.1232                    | 0.1249                    |
| S2   | 16.87   | 1193.40      | 16h02m04.2449s | −11d17m17.1874s | 0.153                     | 0.173                    | 0.1232                    | 0.1249                    |
| S3   | 15.40   | 1222.75      | 16h02m04.2602s | −11d17m17.5078s | 0.103                     | 0.176                    | 0.1232                    | 0.1249                    |
| S4   | 9.93    | 1216.80      | 16h02m04.2661s | −11d17m17.3666s | 0.333                     | 0.247                    | 0.1232                    | 0.1249                    |
| S5   | 6.70    | 1276.50      | 16h02m04.2558s | −11d17m17.9337s | 0.214                     | 0.269                    | 0.1232                    | 0.1249                    |
| C1   | 19.03   | 1267.50      | 16h02m04.2734s | −11d17m17.3078s | 0.041                     | 0.071                    | 0.2263                    | 0.2090                    |
| Name  | MJD                      | DM   | Width (ms) | Fluence (Jy ms) | Center (GHz) | FWHM (MHz) |
|-------|--------------------------|------|------------|-----------------|--------------|------------|
| L1†   | 59051.04766857(9)        | 1222 | 4\(^{+11}\)\(_{-1}\) | 1.73\(^{+0.36}\)\(_{-0.03}\) | 300\(^{+500}\)\(_{-100}\) |
| L2    | 59053.10458030(6)        | 1246 | 1.8\(^{+0.3}\)\(_{-0.2}\) | 1.75\(^{+0.01}\)\(_{-0.01}\) | 250\(^{+50}\)\(_{-30}\) |
| L3    | 59053.09732720(2)        | 1240 | 1.3\(^{+0.2}\)\(_{-0.2}\) | 3.13\(^{+0.04}\)\(_{-0.07}\) | 1000\(^{+200}\)\(_{-100}\) |
| S1†   | 59091.96043097(4)        | 1270 | 0.63\(^{+0.05}\)\(_{-0.05}\) | 3.751\(^{+0.008}\)\(_{-0.008}\) | 240\(^{+30}\)\(_{-20}\) |
| S2    | 59091.95607912(2)        | 1100 | 0.8\(^{+1.2}\)\(_{-0.6}\) | 2.3\(^{+0.1}\)\(_{-0.1}\) | 340\(^{+20}\)\(_{-20}\) |
| S3    | 59091.96349924(4)        | 1185 | 0.7\(^{+0.8}\)\(_{-0.5}\) | 3.5\(^{+0.03}\)\(_{-0.03}\) | 530\(^{+80}\)\(_{-70}\) |
| S4    | 59091.94352882(2)        | 1260 | 0.7\(^{+0.7}\)\(_{-0.5}\) | 3.5\(^{+0.03}\)\(_{-0.03}\) | 530\(^{+80}\)\(_{-70}\) |
| S5†   | 59091.96684707(6)        | 1280 | \(\leq 4\(^{+1}\)\(_{-1}\)\) | – | – |
| C1    | 59107.92721381(1)        | 1300 | 0.11\(^{+0.07}\)\(_{-0.07}\) | 0.36\(^{+0.03}\)\(_{-0.03}\) | 5.266\(^{+0.01}\)\(_{-0.008}\) | 230\(^{+30}\)\(_{-20}\) |

**Extended Data** | **Table 4**: Spectro-temporal properties of the VLA bursts. The label in the first column shows the frequency band of observation, followed by the burst number. 1σ errors on the fits are shown on superscript and subscript of each value in the table. For MJD, the error on the last significant digit is shown in parenthesis. MJD is referenced to the solar system barycenter and corrected for dispersion delay to the top of the observing band. As mentioned in text, width values here should be considered as upper limits. Bursts that extend beyond the observable band are marked with † to indicate that the fitted parameters (fluence and FWHM) could be unconstrained.
### Supplementary

**Table 1 : The properties of the 79 FRB 190520B bursts detected by FAST.**

| Burst ID  | Burst time   | DM  | Pulse width | Scatter tail | Fluence | Energy |
|-----------|--------------|-----|-------------|--------------|---------|--------|
|           | (MJD)        | (pc cm$^{-3}$) | (ms) | (ms) | (mJy ms) | ($\times 10^{37}$ erg) |
| P1        | 58623.716958197 | 1238.6 (20) | 8.7 (8) | - | 75.0 ± 3.0 | 9.1 (0) |
| P2        | 58623.716958197 | 1238.6 (20) | 16.4 (6) | - | 30.0 ± 2.0 | 3.6 (0) |
| P3        | 58623.716958197 | 1238.6 (20) | 7.1 (8) | - | 53.0 ± 3.0 | 6.4 (0) |
| P4        | 58623.717421629 | 1238.6 (20) | 7.3 (10) | - | 53.0 ± 4.0 | 6.2 (0) |
| P5        | 58963.766862939 | 1209.1 (10) | 10.4 (2) | - | 65.7 ± 6.7 | 8.0 (0) |
| P6        | 58963.790991383 | 1209.1 (10) | 10.2 (17) | 13.1(23) | 52.8 ± 5.4 | 6.4 (0) |
| P7        | 58991.684351079 | 1214.2 (5) | 20.3 (4) | - | 107.1 ± 18.5 | 13.0 (2) |
| P8        | 58991.686137870 | 1214.2 (5) | 22.8 (83) | 11.5(68) | 100.5 ± 10.5 | 12.2 (1) |
| P9        | 58991.686875951 | 1214.2 (5) | 9.2 (2) | - | 81.0 ± 12.7 | 9.8 (1) |
| P10       | 58991.704636888 | 1214.2 (5) | 19.5 (17) | 3.6(8) | 108.3 ± 12.4 | 13.1 (1) |
| P11       | 58991.704638485 | 1214.2 (5) | 9.7 (7) | - | 42.9 ± 0.8 | 5.2 (0) |
| P12       | 58991.717697335 | 1214.2 (5) | 11.9 (11) | 10.3(12) | 122.9 ± 21.4 | 14.9 (2) |
| P13       | 58991.717878516 | 1214.2 (5) | 14.3 (40) | 5.1(25) | 58.9 ± 10.5 | 7.1 (1) |
| P14       | 58991.718217265 | 1214.2 (5) | 11.8 (15) | - | 63.7 ± 6.8 | 7.7 (0) |
| P15       | 58991.718217670 | 1214.2 (5) | 17.5 (3) | - | 39.3 ± 4.2 | 4.8 (0) |
| P16       | 58991.718218082 | 1214.2 (5) | 20.2 (22) | 12.6(19) | 153.2 ± 28.3 | 18.6 (3) |
| P17       | 58991.735450006 | 1214.2 (5) | 30.2 (5) | - | 138.6 ± 21.7 | 16.8 (2) |
| P18       | 58991.750640038 | 1214.2 (5) | 17.7 (13) | - | 60.9 ± 9.5 | 7.4 (1) |
| P19       | 58991.750640790 | 1214.2 (5) | 20.2 (5) | - | 81.3 ± 14.5 | 9.9 (1) |
| P20       | 59060.484475154 | 1209.1 (5) | 13.5 (13) | 11.3(14) | 241.2 ± 12.9 | 29.3 (1) |
| P21       | 59060.507858658 | 1209.1 (5) | 7.3 (9) | 9.3(12) | 170.2 ± 8.6 | 20.7 (1) |
| P22       | 59060.525960600 | 1209.1 (5) | 17.3 (24) | 7.6(16) | 167.5 ± 14.8 | 20.3 (1) |
### Table 1: The properties of the 79 FRB 190520B bursts detected by FAST.

| Burst ID \(d\) | Burst time \(b\) (MJD) | DM \(c\) (pc cm\(^{-3}\)) | Pulse width (ms) | Scatter tail \(d\) (ms) | Fluence (mJy ms) | Energy \(e\) \((\times10^{37}\text{erg})\) |
|-----------------|------------------------|-----------------------------|------------------|--------------------------|----------------|------------------|
| P23             | 59061.512755579         | 1209.1 (6)                  | 8.5 (1)          | -                        | 48.3 ± 6.3     | 5.9 (0)          |
| P24             | 59061.512755780         | 1209.1 (6)                  | 10.0 (23)        | 4.7 (17)                 | 129.5 ± 16.8   | 15.7 (2)         |
| P25             | 59061.516277966         | 1209.1 (6)                  | 7.1 (6)          | -                        | 29.8 ± 2.7     | 3.6 (0)          |
| P26             | 59061.516278904         | 1209.1 (6)                  | 7.5 (4)          | -                        | 49.3 ± 5.9     | 6.0 (0)          |
| P27             | 59061.516279436         | 1209.1 (6)                  | 11.4 (8)         | -                        | 49.0 ± 4.7     | 6.0 (0)          |
| P28             | 59061.524341261         | 1209.1 (6)                  | 10.7 (8)         | 10.4 (9)                 | 122.4 ± 16.3   | 14.8 (1)         |
| P29             | 59061.535633328         | 1209.1 (6)                  | 14.0 (4)         | -                        | 84.4 ± 8.3     | 10.2 (1)         |
| P30             | 59061.536568858         | 1209.1 (6)                  | 21.9 (17)        | -                        | 72.0 ± 9.4     | 8.7 (1)          |
| P31             | 59061.536569628         | 1209.1 (6)                  | 19.0 (14)        | 14.0 (13)                | 122.1 ± 41.5   | 14.8 (5)         |
| P32             | 59061.537903820         | 1209.1 (6)                  | 23.9 (27)        | 4.9 (13)                 | 65.9 ± 8.2     | 8.0 (0)          |
| P33             | 59061.539298620         | 1209.1 (6)                  | 9.9 (3)          | -                        | 73.6 ± 9.2     | 8.9 (1)          |
| P34             | 59061.541828100         | 1209.1 (6)                  | 19.8 (20)        | 8.7 (10)                 | 212.2 ± 28.1   | 25.8 (3)         |
| P35             | 59067.467544345         | 1202.8 (6)                  | 15.2 (76)        | 5.4 (46)                 | 67.4 ± 8.4     | 8.2 (1)          |
| P36             | 59067.486738799         | 1202.8 (6)                  | 14.9 (22)        | 17.8 (29)                | 131.4 ± 14.1   | 15.9 (1)         |
| P37             | 59067.486739378         | 1202.8 (6)                  | 33.1 (7)         | -                        | 146.7 ± 18.0   | 17.8 (2)         |
| P38             | 59067.502691880         | 1202.8 (6)                  | 14.3 (6)         | -                        | 134.7 ± 3.1    | 16.3 (0)         |
| P39             | 59067.509899127         | 1202.8 (6)                  | 12.2 (18)        | 10.3 (17)                | 122.2 ± 8.0    | 14.8 (0)         |
| P40             | 59067.535246460         | 1202.8 (6)                  | 7.6 (2)          | -                        | 74.0 ± 9.5     | 9.0 (1)          |
| P41             | 59069.495909561         | 1190.2 (11)                 | 16.8 (5)         | -                        | 143.0 ± 10.6   | 17.4 (1)         |
| P42             | 59069.501196109         | 1190.2 (11)                 | 18.7 (1)         | -                        | 291.6 ± 14.6   | 35.4 (1)         |
| P43             | 59069.514994796         | 1190.2 (11)                 | 12.2 (15)        | 11.6 (17)                | 192.7 ± 13.0   | 23.4 (1)         |
| P44             | 59071.472522775         | 1200.0 (11)                 | 5.2 (3)          | -                        | 79.0 ± 1.9     | 9.6 (0)          |
| P45             | 59071.472523007         | 1200.0 (11)                 | 7.2 (7)          | -                        | 66.8 ± 1.6     | 8.1 (0)          |
Supplementary | Table 1: The properties of the 79 FRB

190520B bursts detected by FAST.

| Burst ID<sup>a</sup> | Burst time<sup>b</sup> (MJD) | DM<sup>c</sup> (pc cm<sup>−3</sup>) | Pulse width (ms) | Scatter tail<sup>d</sup> (ms) | Fluence (mJy ms) | Energy<sup>e</sup> (×10<sup>37</sup> erg) |
|----------------------|-----------------------------|---------------------------------|------------------|-----------------------------|----------------|-----------------|
| P46 59071.491696655  | 1200.0 (11)                | 10.4 (20)                      | 4.9(15)          | 184.5 ± 4.5                | 22.4 (0)     |
| P47 59073.496887082  | 1197.0 (7)                  | 7.8 (2)                        | -                | 107.7 ± 9.5                | 13.1 (1)     |
| P48 59073.515256071  | 1197.0 (7)                  | 18.7 (6)                       | -                | 147.7 ± 2.0                | 17.9 (0)     |
| P49 59073.515256881  | 1197.0 (7)                  | 11.1 (7)                       | -                | 57.9 ± 4.8                 | 7.0 (0)      |
| P50 59075.454353002  | 1210.6 (6)                  | 24.9 (1)                       | -                | 313.0 ± 19.4               | 38.0 (2)     |
| P51 59075.454862469  | 1210.6 (6)                  | 22.0 (1)                       | -                | 209.8 ± 12.8               | 25.5 (1)     |
| P52 59075.472181012  | 1210.6 (6)                  | 14.0 (5)                       | -                | 114.0 ± 6.8                | 13.8 (0)     |
| P53 59075.484186304  | 1210.6 (6)                  | 6.0 (0)                        | -                | 157.7 ± 16.5               | 19.1 (2)     |
| P54 59075.496463775  | 1210.6 (6)                  | 16.7 (4)                       | -                | 83.6 ± 8.2                 | 10.1 (0)     |
| P55 59077.448938437  | 1210.6 (6)                  | 11.9 (5)                       | -                | 103.4 ± 7.0                | 12.5 (0)     |
| P56 59077.448939131  | 1218.6 (8)                  | 14.4 (7)                       | -                | 107.7 ± 5.9                | 13.1 (0)     |
| P57 59077.449538432  | 1218.6 (8)                  | 13.4 (17)                      | 10.6(16)         | 199.4 ± 10.4               | 24.2 (1)     |
| P58 59077.449939184  | 1218.6 (8)                  | 5.4 (26)                       | -                | 148.6 ± 7.1                | 18.0 (0)     |
| P59 59077.449939372  | 1218.6 (8)                  | 9.6 (29)                       | -                | 121.1 ± 11.8               | 14.7 (1)     |
| P60 59077.460100338  | 1218.6 (8)                  | 13.0 (23)                      | 13.5(28)         | 132.3 ± 1.8                | 16.1 (0)     |
| P61 59077.460503968  | 1218.6 (8)                  | 10.3 (18)                      | 10.6(21)         | 94.1 ± 5.1                 | 11.4 (0)     |
| P62 59077.466295203  | 1218.6 (8)                  | 11.7 (2)                       | -                | 156.7 ± 10.1               | 19.0 (1)     |
| P63 59077.468715062  | 1218.6 (8)                  | 18.4 (35)                      | 7.6(18)          | 128.9 ± 9.4                | 15.6 (1)     |
| P64 59077.469903193  | 1218.6 (8)                  | 11.2 (10)                      | 11.3(12)         | 152.0 ± 7.4                | 18.5 (0)     |
| P65 59077.475047947  | 1218.6 (8)                  | 11.0 (17)                      | 8.3(16)          | 107.4 ± 6.9                | 13.0 (0)     |
| P66 59077.475330491  | 1218.6 (8)                  | 14.0 (8)                       | 12.9(9)          | 205.5 ± 11.7               | 24.9 (1)     |
| P67 59077.477447949  | 1218.6 (8)                  | 2.0 (1)                        | -                | 70.0 ± 2.8                 | 8.5 (0)      |
| P68 59077.485451841  | 1218.6 (8)                  | 14.3 (1)                       | -                | 332.8 ± 7.3                | 40.4 (0)     |
Table 1: The properties of the 79 FRB 190520B bursts detected by FAST.

| Burst ID<sup>a</sup> | Burst time<sup>b</sup>  | DM<sup>c</sup>  | Pulse width | Scatter tail<sup>d</sup> | Fluence | Energy<sup>e</sup> |
|---------------------|------------------------|----------------|-------------|------------------------|---------|-----------------|
| P69                 | 59077.485451957        | 1218.6 (8)     | 14.4 (1)    | -                      | 262.3 ± 15.9 | 31.8 (1)        |
| P70                 | 59077.490027004        | 1218.6 (8)     | 8.4 (4)     | -                      | 132.4 ± 2.9  | 16.1 (0)        |
| P71                 | 59077.491413589        | 1218.6 (8)     | 10.3 (3)    | -                      | 115.5 ± 5.0  | 14.0 (0)        |
| P72                 | 59077.497806611        | 1218.6 (8)     | 15.3 (22)   | 10.7 (21)              | 138.3 ± 9.7  | 16.8 (1)        |
| P73                 | 59077.497957805        | 1218.6 (8)     | 13.6 (4)    | -                      | 89.5 ± 5.6   | 10.9 (0)        |
| P74                 | 59077.498960966        | 1218.6 (8)     | 4.6 (7)     | 11.8 (15)              | 94.2 ± 6.0   | 11.4 (0)        |
| P75                 | 59089.428163703        | 1186.7 (25)    | 11.2 (2)    | -                      | 112.2 ± 3.4  | 13.6 (0)        |
| P76                 | 59089.436165435        | 1186.7 (25)    | 13.3 (6)    | -                      | 83.2 ± 2.9   | 10.1 (0)        |
| P77                 | 59111.370525959        | 1183.3 (17)    | 20.6 (6)    | -                      | 99.3 ± 11.9  | 12.0 (1)        |
| P78                 | 59111.370526098        | 1183.3 (17)    | 6.7 (1)     | -                      | 106.5 ± 8.0  | 12.9 (0)        |
| P79                 | 59111.370978062        | 1183.3 (17)    | 14.6 (5)    | -                      | 98.1 ± 9.6   | 11.9 (1)        |

<sup>a</sup> The burst ID are from 1 to 79. The P1 to P4 were detected in the drift scan mode. P4 to P79 were detected in the tracking mode.

<sup>b</sup> Arrival time of burst at the solar system barycenter. They are corrected to the frequency of 1.5 GHz in the international celestial reference System (ICRS).

<sup>c</sup> All the bursts detected on the same day are assigned the best fit DM value of the burst from that day. The error is for the last digit.

<sup>d</sup> We only report scattering timescales for bursts with an
obvious scattering tail.

* Energy here refers to equivalent isotropic energy.