The Environment and Constraints on the Mass of FRB 190520B

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ABSTRACT
Recent observations (Anna-Thomas, Connor, Burke-Spolaor et al. 2022; Dai, Feng, Yang et al. 2022) of FRB 20190520B have revealed rapid fluctuation of its Dispersion Measure within apparently fixed bounds, as well as a reversal of its Rotation Measure. The fluctuations of Dispersion Measure are uncorrelated with the intervals between bursts, setting upper bounds ~ 10 s on any characteristic time scale of the dispersing region; it must be very compact. Measurements of the full dependence of the dispersive time delay on frequency may determine the actual electron density and the size of this region. It is possible to set a lower bound on the mass of the FRB source from constraints on the size of the dispersing region and its time scale of variation. Comparison of the variations of DM and RM leads to an estimate of the magnetic field ~ 500 μG.

Key words: radio continuum, transients: fast radio bursts, accretion, accretion discs, stars: black holes, stars: magnetars

1 INTRODUCTION
Anna-Thomas, Connor, Burke-Spolaor et al. (2022); Dai, Feng, Yang et al. (2022) discovered rapid fluctuations in the Rotation Measure (RM) of FRB 20190520B and a reversal of its Dispersion Measure (DM). In 113 bursts observed over 237 days DM ranged between 1180 and 1230 pc-cm$^{-3}$. 67 bursts observed over two hours on MJD 59373 showed DM ranging from 1190 to 1230 pc-cm$^{-3}$, suggesting a rapidly varying and necessarily very compact near-source region contributing 0–40 pc-cm$^{-3}$. The nearly constant remainder is plausibly contributed by the intergalactic medium, Galactic plasma, and more distant (from the source) portions of the host galaxy.

Typical observed bursts have peak flux densities ~ 1 Jy and durations 1–2 ms, corresponding to a duty factor ~ 10$^{-5}$. This could be the result of isotropic emission ~ 10$^{-5}$ of the time, continual emission into a wandering ~ 10$^{-4}$ sterad beam (readily interpreted as the result of radiation by relativistic charge bunches with Lorentz factors ~ 100), or some intermediate combination. At the redshift $z = 0.241$ and observed bandwidth $\Delta \nu \sim 300$ MHz the mean power is ~ 3 × 10$^{36}$ ergs/s.

2 BOUNDS ON CHARACTERISTIC TIME SCALES
Fig. 1 shows the differences in |DM| between successive bursts observed on MJD 59373 vs. their separation in time.

It is evident that there is no correlation of |ΔDM| with Δt for intervals as short as 1.0 × 10$^{-4}$ d (8.64 s), the shortest interval in the data of Dai, Feng, Yang et al. (2022), aside from three intervals ≤ 35 ms that may be attributable to burst substructure. On the line of sight to the FRB, likely surrounding it and causally associated with it, is a turbulent region whose contribution to the DM varies from zero to 40 pc-cm$^{-3}$.

The data of Fig. 1 set an upper bound $t \lesssim 10$ s on the characteristic time scale of this compact, near-source, turbulent region. A lower bound on the correlation time ~ 35 ms may be estimated on the basis of the small or zero [ΔDM] within burst substructure, or between bursts separated by such small Δt. The remaining 1190 pc-cm$^{-3}$ is attributed to the intergalactic medium, our Galaxy, and an essentially unvarying (during the two hours of observation on MJD 59373, and only slightly varying over the entire 237 day campaign), likely extended, host galaxy region estimated to contribute about 900 pc-cm$^{-3}$ (Niu et al. 2021).

3 THE TURBULENT REGION
The turbulent region must be able to contribute $n_e R = DM \approx 40$ pc-cm$^{-3} \approx 1.2 \times 10^{20}$ cm$^{-2}$, where $n_e$ is its characteristic electron density and $R$ its size (radius if the FRB is at its center).

An upper bound on $n_e$ and lower bound on $R$ can be set from the fact that Dai, Feng, Yang et al. (2022) observed at frequencies 3000–3500 GHz; propagation requires that the the plasma frequency be lower than the frequency of observation. Then

$$n_e \leq \frac{\pi \nu^2 m_e}{e^2} \approx 1.1 \times 10^{11}$ cm$^{-3}$, \tag{1}$$

where $\nu \approx 3 \times 10^{9}$ s$^{-1}$ is the frequency of the observed radiation that has passed through the dispersing cloud. There

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The shortest time scale variations involve only |ΔDM| ≈ 12 pc-cm⁻³, insignificant compared to the scatter of ΔDM. Intervals with Δt > 0.002 d are not shown. Two overlapping points at the origin (intervals of 5 ms and 23 ms between pairs of bursts with $\Delta DM = 0.0 \pm 0.6 \text{pc-cm}^{-3}$) likely represent substructure of the same burst. The point on the ordinate with nominally significant $|\Delta DM| = 2.8 \pm 0.6 \text{pc-cm}^{-3}$ and $\Delta t = 4 \times 10^{-7} \text{d}$ (35 ms) may also represent substructure.

appears to be a low-frequency cutoff around 3 GHz in the bursts observed by Dai, Feng, Yang et al. (2022), suggesting that Eq. 1 may be an actual estimate of $n_e$ rather than only a bound.

If the frequency of observation $\nu$ is close to the plasma frequency of the dispersing cloud, then the dispersion delay is no longer quantitatively proportional to $\nu^{-2}$, but has a more complex dependence on frequency:

$$\Delta t = \int \frac{d\ell}{c} \frac{1}{2} \frac{\omega_p^2}{\omega^2} \left(1 + \frac{3}{4} \frac{\omega_p^2}{\omega^2} + \cdots \right),$$

where $\omega_p = \sqrt{4\pi n_e e^2/m_e}$. If the higher order term(s) could be fit to the data, $n_e$ would be measured directly and $R$ inferred unambiguously.

From the definition of DM

$$R \equiv \frac{|\Delta DM|}{n_e},$$

The shortest time scale variations involve only $|\Delta DM| \approx 12 \text{pc-cm}^{-3}$, the turbulent region is likely heterogeneous, with a greatest DM of 40 pc-cm⁻³ but the most rapidly varying part contributing less. Then, using Eq. 1,

$$R \geq 3 \times 10^8 \text{cm}.$$  

If the turbulent region is gravitationally bound to, or infalling into, a mass $M$, then it is possible to bound this mass

$$GM \sim \frac{R^3}{t^2} \geq 4 \times 10^{23} \text{cm}^3 \text{s}^{-2},$$

or

$$M \gtrsim 5 \times 10^{30} \text{g}.$$  

If $t$ is taken as the shortest burst interval $\sim 35 \text{ms}$ with nominally significant non-zero $\Delta DM$ then the lower bound on $M$ would be about five orders of magnitude greater, or $\sim 200M_\odot$. However, this would be a slender reed on which to base such a remarkable inference.

Some of the earlier observations of Niu et al. (2021) were made at about 1500 MHz, but may have been taken at an epoch when the rapidly varying near-source plasma was less dense. Niu et al. (2021) did not report a rapidly varying DM, so the preceding analysis may not be applicable. However, if it is applicable and the $|\Delta DM|$ are comparable, the implied $n_e \lesssim 3 \times 10^{19} \text{cm}^{-3}$, $R \gtrsim 1.3 \times 10^9 \text{cm}$ (taking the $|\Delta DM| = 12 \text{pc-cm}^{-3}$ corresponding to the shortest $\Delta t$, rather than the full range $|\Delta DM| = 40 \text{pc-cm}^{-3}$), and the implied $M \gtrsim 4 \times 10^{32} \text{g}$.

An independent bound can be derived from the requirement that the free-free optical depth (Spitzer 1962) be $\lesssim 1$. Using Eq. 3 to eliminate $n_e$ in favor of DM,

$$R > 5 \times 10^{10} \left(\frac{\text{DM}}{12 \text{pc-cm}^{-3}}\right)^2 T_6^{-3/2} \text{cm},$$

where $T_6 \equiv T/(10^6 \text{K})$. Combining this with the causality constraint $R < ct \approx 3 \times 10^7 \text{cm}$ yields

$$T_6 > 0.3 \left(\frac{\text{DM}}{12 \text{pc-cm}^{-3}}\right)^{4/3}.$$  

This is a physically possible condition, but indicates a hotter plasma than the filaments of known supernova remnants. However, the estimated mean power of $3 \times 10^{36} \text{ergs/s}$, subject only to the distance constraints of Eqs. 4, 7 and the causality limit $R \leq ct$, permits much higher energy density and temperature. The alternative of dispersion by the relativistic particles of a pulsar wind nebula fails because they are insufficiently numerous to give significant dispersion, and are also affected by the relativistic increase of effective mass.

4 MAGNETIC FIELD

The magnetic field in the dispersing region may be estimated:

$$|B| \sim 1.23 \left|\frac{\Delta RM}{\Delta DM}\right| \mu G \sim 300 \mu G,$$

where RM is in the usual units of radians/m², DM is in pc-cm⁻³, and $B_0$ is the electron density-weighted mean component along the line of sight.

An alternative, but numerically similar, estimate may be obtained by comparing the DM and RM of bursts 2 and 3 in Table 1 of Dai, Feng, Yang et al. (2022). These bursts occurred on MJD 59373 and the two methods of estimating RM agree (burst 1 occurred on the same day, but the two estimates of RM disagree by four times their formal error, an issue also for burst 5 on MJD 59400 and burst 7 on MJD.
Between bursts 2 and 3 $|\Delta R M| = 800 \pm 43\, \text{m}^2\text{rad}$ and $|\Delta D M| = 1.8 \pm 0.5\, \text{pc-cm}^{-3}$, leading to $|B_\parallel| = 546 \pm 164\, \mu\text{G}$. \hfill (10)

The uncertainty chiefly results from the large fractional uncertainty in $|\Delta D M|$. The fact that DM varies coherently shows that there are not a large number of independent regions contributing to the DM. If this is also true for the RM then Faraday rotation in regions with opposite signs of $B_\parallel$ does not efficiently cancel and Eq. 9 estimates the actual field magnitude. This is not proven because a region homogeneous in $n_e$ may have subregions with cancelling $B_\parallel$; Eq. 9 is properly only a lower bound on the field magnitude. The field estimated in Eq. 9 is much smaller than the fields of $3-17\, \text{mG}$ similarly estimated for the environment of FRB 121102 (Katz 2021). This results from the much larger $|\Delta D M|$ measured for FRB 190520B, but why this should be so is unclear.

### 5 DISCUSSION

The mass bound of Eqs. 5, 6 isn’t yet interesting, because it is hard to imagine a FRB source with a mass less than the minimum mass of a neutron star, about $1.4 M_\odot$. However, future observations might well produce lower estimates of the characteristic time $t$ or (if a rapidly varying DM were observed at lower frequencies) larger estimates of the characteristic size $R$ from the requirement the plasma be dilute enough to transmit radio waves of the observed frequency and yet provide the measured $|\Delta D M|$. These might provide useful constraints on masses and models.

One conclusion can be drawn from the rapid variations of DM shown in Fig. 1 without modeling the dispersing region: It cannot be larger than $ct \sim 3 \times 10^{11}\, \text{cm}$. This excludes models in which the dispersion is produced in a supernova remnant or other extended cloud. It also argues against models in which the FRB is produced far ($\gtrsim ct$) from a central compact source unless the dispersing medium is heterogeneous on scales $\ll ct$ and most of the dispersion is within $\ll ct$ of the emission sites of the individual bursts (the medium must be extremely clumpy with bursts and their dispersion produced in separate and uncorrelated clumps).

The bound $R \lesssim ct$ sets a lower bound on $n_e$, independent of any assumptions about the dynamics of the dispersing medium:

$$n_e \gtrsim \frac{|\Delta D M|}{ct} \sim 3 \times 10^8\, \text{cm}^{-3},$$

consistent with Eq. 1. This excludes the environment of a pulsar or magnetar, swept clean of thermal plasma by its wind (relativistic plasma is ineffective at dispersing radio emissions). Supernova remnants have dense filaments, but they would be expected to obscure the central object with a low duty factor, while FRB 190520B appears to be behind dispersing matter much of the time; its excess source region DM is broadly distributed (Fig. 1) from 0 to 40 pc-cm$^{-3}$ rather than having rare excursions from low values. Eq. 11 may point to an accretion flow (Katz 2022).

### DATA AVAILABILITY

This theoretical study did not generate any new data.

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