FRB 190520B—A FRB in a Young Supernova Remnant?

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ABSTRACT
FRB 190520B, a repeating FRB near-twin of FRB 121102, was discovered (Niu et al. 2021) to have a dispersion measure excess over the intergalactic and Galactic contributions of about 900 pc-cm$^{-3}$, attributable to its host galaxy or near-source environment. This excess varies on a time scale of $\sim 30$ y and might be explained by a supernova remnant no more than a few decades old. A magnetic field in equipartition with the remnant’s expansion would be $\sim 1$ G. I suggest the use of baseband data to measure very large rotation measures.

Key words: radio continuum, transients: fast radio bursts, stars: neutron, supernova remnants

1 INTRODUCTION
The recently discovered (Niu et al. 2021) FRB 190520B is, in many respects, a near-twin of FRB 121102. Both are identified with dwarf star-forming galaxies with similar redshifts (0.241 and 0.193, respectively), repeat frequently, and are accompanied by steady persistent radio sources (PRS) of similar strength ($\sim 3\times10^{29}$ erg/(s-Hz) at GHz frequencies). Neither’s bursts have been found to repeat periodically (Zhang et al. 2018; Aggarwal et al. 2021; Niu et al. 2021), although the activity of FRB 121102 is modulated with a 160 d period (Rajwade et al. 2020; Cruces et al. 2021). Insufficient data exist to decide whether FRB 190520B is similarly modulated.

FRB 190520B is unique among FRB in having a large contribution to its dispersion measure (DM) in addition to the known or estimated intergalactic and Galactic contributions, that is far in excess of their uncertainties (Fig. 3 of Niu et al. 2021). Other FRB are suspected of having such excess DM, but they are an order of magnitude smaller and might be attributed to underestimated uncertainties of the intergalactic or Galactic contributions. The excess DM of FRB 190520B of $\approx 900$ pc-cm$^{-3}$ ($\approx 2.7 \times 10^{21}$ cm$^{-2}$) is therefore attributed to matter cosmologically local to the FRB: an interstellar cloud in the host galaxy, its halo (unlikely for the dwarf galaxy host) or the immediate environment of the FRB.

This paper discusses these hypotheses, rejects the interstellar cloud (Sec. 2; an appendix discusses the case of a cloud supported by thermal pressure) and attributes the excess DM to a young dense supernova remnant (SNR) enveloping the FRB (Sec. 3). If the observed mean decrease of the DM (ED) (Niu et al. 2021) is attributed to the expansion of a SNR (Katz 2016; Margalit & Metzger 2018; Piro & Gaensler 2018), its age is bounded as $\lesssim 30$ y.

However, FRB 121102, whose DM is increasing (Hilmarsson et al. 2020), is not consistent with that picture. The rapid fluctuations of the DM of FRB 190520B, if not the result of intra-burst frequency drift, must be attributed to turbulent motion of clumps or filaments within the SNR, as discussed (Katz 2021) for FRB 121102. This casts doubt on the explanation of the mean decrease, whose inference depends on a single datum, as a consequence of SNR expansion, and makes it difficult to relate this to global properties of a putative SNR.

2 THE DISPERSING CLOUD
2.1 Parameters
An assumption of fully ionized pure hydrogen is an adequate approximation. From the measured DM the density $n$ and size $r$ of the cloud can be found as functions of its mass $M$:

$$\frac{4\pi}{3} n r^3 m_p = M,$$

where $m_p$ is the mass of a proton. Using the definition $\text{DM} \equiv n r$:

$$r = \sqrt{\frac{3M}{4\pi m_p}} \text{DM}^{-1/2} \approx 3 \times 10^{17} \sqrt{\frac{M}{M_\odot}} \text{ cm}$$

and

$$n = \sqrt{\frac{4\pi m_p}{3}} \frac{M}{M} \text{DM}^{3/2} \approx 8 \times 10^3 \sqrt{\frac{M_\odot}{M}} \text{ cm}^{-3}.$$  

2.2 Emission Measure
Eqs. 2 and 3 may be combined to calculate the emission measure $EM$ if the source region is homogeneous

$$EM \equiv n^2 r \approx 7 \times 10^6 \sqrt{\frac{M_\odot}{M}} \text{ pc-cm}^{-6}.$$  

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⋆ The uncertainty of this value is discussed in detail by Niu et al. (2021) and is unlikely to much exceed ±10%. The conclusions presented here are insensitive to uncertainties of this magnitude, so the uncertainty range is not propagated into the numerical estimates.
Niu et al. (2021) report the $H\alpha$ flux from the host galaxy of FRB 190520B. The $H\alpha$ source is unresolved, so in order to obtain a value for EM they must assume a solid angle for the source. Taking this to be the resolution element 0.25 arc-sec$^2$, they found the $H\alpha$ surface brightness $S = 503 \pm 14$ Rayleigh (denoted $R$).

Comparison to the value inferred from the $H\alpha$ line$^2$ $EM = 3280 T_4^{0.9} \text{pc-cm}^{-6} (S/500R) = 1.01 \times 10^{22} T_4^{0.9} \text{cm}^{-3} (S/500R)$ (Niu et al. 2021) indicates either a cloud of $M \sim 6 \times 10^6 (S/500R)^{-2} T_4^{-1.8} M_\odot$ or that the $H\alpha$ line is not produced by the same source that produces the DM. The sensitive dependence of $M$ on the uncertain $S$ limits the significance of this estimate.

Alternatively, Eq. 4 may be inverted to estimate $r$, using the EM inferred from the $H\alpha$ line:

$$r = \frac{DM^2}{EM} \approx 250 T_4^{-0.9} (S/500R)^{-1} \text{pc},$$

implying, from Eqs. 2 and 3,

$$M \sim 6 \times 10^6 T_4^{1.8} (S/500R)^{-2} M_\odot$$

and

$$n \sim 3 T_4^{0.9} (S/500R) \text{cm}^{-3}.$$ (7)

If $S \sim 500R$ these are plausible values for the mass and density of ionized gas in a star-forming galaxy. However, they are very sensitive to $S$ and hence to the unknown angular size of the $H\alpha$ source. Large $n$ and smaller $M$ are consistent with the observations if $S$ is large. $H\alpha$ emission from very dense clouds is limited by self-absorption, invalidating the assumed relation (Niu et al. 2021) between $S$ and EM.

The value of $r$ inferred from the EM is inconsistent with the observed rapid variation of DM unless $S \gg 500R$, which would require that the $H\alpha$ source be very under-resolved. The paradox may be resolved in at least two ways:

(i) Most of the DM of the FRB is produced in the cloud that emits the $H\alpha$ radiation, but the variable part of the DM is produced by a much smaller cloud whose DM is undetermined (but must be at least as large as the amplitude of variation, $\Delta DM \sim 30 \text{pc-cm}^{-3}$);

(ii) The cloud that produces the $H\alpha$ radiation is not the source of the host galaxy contribution to the DM of the FRB, either because it is not on the line of sight, or because its (undetermined) DM is much less than 900 pc-cm$^{-3}$. This is the most economical explanation: the $H\alpha$ source is a large, low density, interstellar cloud unrelated to the FRB.

If the second hypothesis is correct, the observed EM does not constrain the source of the DM. Because 900 pc-cm$^{-3}$ exceeds the DM of known galactic clouds, another source, such as a SNR, must be sought.

4 MAGNETIC STRESS AND ROTATION MEASURE

If there is a magnetic stress comparable to the characteristic hydrodynamic stress

$$\frac{B^2}{8\pi} \sim \frac{nm_p v^2}{t} \sim \frac{\Delta DM m_p v}{t} \sim 0.1 \frac{v_8}{t_5} \text{erg cm}^{-3}$$

and

$$B \sim 1.5 \sqrt{\frac{v_8}{t_5}} \text{G}.$$ (10)

For plausible $v_8 \sim 1$ and the observed $t_5 \sim 1$ the field $B \sim 1 \text{G}$. The rotation measure

$$RM \sim \frac{e^3}{2\pi m_e c^2} \Delta DM B \sim 3 \times 10^7 \sqrt{\frac{v_8}{t_5}} \text{radian m}^{-2}.$$ (11)

This RM is so large that it is difficult to measure directly because of intra-channel Faraday rotation, but could be manifested as the observed absence of linear polarization (Niu et al. 2021). It might be measurable with high rate sampling of the baseband signal (Kocz et al. 2015; Gajjar et al. 2018; Lynch et al. 2019, 2020; Michilli et al. 2021; Mckinnon et al. 2021). The dispersive time delay

$$t = \frac{DM}{2\pi m_e c} v^{-2},$$ (12)

where DM is in units of electrons/cm$^2$. The birefringent rotation angle

$$\phi = RM c^2 v^{-2},$$ (13)
where \( \phi \) is in units of radian/cm\(^2\). Eliminating the frequency \( \nu \),

\[
\phi = \frac{\text{RM}}{\text{DM}} \frac{2\pi m_e c^3}{e^2} t
\]

and the electric field in the direction of a linearly polarized feed would have the time dependence

\[
E_{\parallel}(t) \propto F(t) \sin(\phi + \phi_0),
\]

where \( F(t) \) is a comparatively slowly varying function describing the envelope of the burst intensity and \( \phi_0 \) a fixed phase offset.

The Fourier transform of \( E_{\parallel}(t) \) would have an amplitude peak at the angular frequency

\[
\omega_{\text{pol}} = \frac{\text{RM}}{\text{DM}} \frac{2\pi m_e c^3}{e^2} \frac{10^6 \text{ pc} \cdot \text{cm}^{-3}}{\text{DM}} \approx 2.16 \times 10^{14} \text{ s}^{-1}
\]

and the transform of \( |E_{\parallel}(t)| \) (proportional to the intensity) would peak at \( 2\omega_{\text{pol}} \). The factor \( \omega_0 \equiv 2\pi m_e c^3/e^2 = 6.68 \times 10^{13} \text{ s}^{-1} \) (the energy \( \hbar \omega_0 = 2\pi m_e c^2/\alpha \), where \( \alpha \) is the fine-structure constant). These peaks are broadened by the spectral width of \( F(t) \).

5 DISCUSSION

The data may be explained if there are two clouds: a large cloud that is the source of the (apparently steady) H\( \alpha \) emission, and a small cloud that produces the large and variable local DM. This second cloud is naturally interpreted as a young SNR in which the FRB is embedded. These clouds may be unrelated.

Unfortunately, if this explanation is correct the measured DM cannot be used to constrain the parameters of the larger cloud, the source of the H\( \alpha \) radiation. Nor can the larger cloud’s EM be used to constrain the parameters of the source of the excess DM.

The inference of an age \( \lesssim 30 \text{ y} \) depends on the assumption that the DM trend fitted in ED Fig. 8 of Niu et al. (2021), largely (but not entirely) dependent on a single early datum, is really a long-term trend, and not the result of accidental fluctuations of the rapidly varying DM. This can soon be tested by new data, but cannot yet be proven or disproven.

The dispersing cloud radius Eq. 2 corresponds to an age \( \approx 10\sqrt{M/M_\odot}/v_\phi \text{ y} \), consistent with the mean decrease of the DM. However, the rapid irregular fluctuations of DM are inconsistent with a simple expanding SNR model, and require appeal to a filamentary structure. The 3\( \sigma \)-significant increase of the 3 GHz flux of the persistent source, in two months, if real, is also inconsistent and inexplicable as the result of dense filaments of thermal gas. Such rapid variations have not been reported in well-studied young (but not as young as estimated here) SNR (Trotter et al. 2017).

DATA AVAILABILITY

This theoretical study did not generate any new data.

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REFERENCES

Aggarwal, K., Agarwal, D., Lewis, E. F., Anna-Thomas, R., Cardinal Tremblay, J., Burke-Spolaor, S., McLaughlin, M. A. & Lorimer, D. R. 2021 arXiv:2107.05658.

Cruces, M., Spitler, L. G., Scholz, P. et al. 2021 MNRAS 500, 448 (arXiv:2008.03461).

Gajjar, V., Siemion, A., MacMohan, D. et al. 2018 Bull. Am. Astr. Soc. 231, 132.02.

Hilmansson, G. H., Michilli, D., Spitler, L. G. et al. 2021 ApJ 908, L10 (arXiv:2009.12135).

Katz, J. I. 2016 ApJ 818, 19 (arXiv:1505.06220).

Katz, J. I. 2017 MNRAS 471, L92 (arXiv:1704.08301).

Katz, J. I. 2019 MNRAS 487, 491 (arXiv:1811.10755).

Katz, J. I. 2020 MNRAS 494, L64 (arXiv:1912.00526).

Katz, J. I. 2021 MNRAS 501, L76 (arXiv:2011.11666).

Kocz, J., Greenhill, L. J., Barsdell, B. R. et al. 2015 J. Astron. Inst. 4, 1550003 (arXiv:1411.3751).

Lynch, R. S., Hawkins, L., McCullough, R. & Ray, J. 2019 Bull. AAS 233, 146.15 (2019AAS ...2331461L).

Lynch, R. S., Hawkins, L., McCullough, R., Ray, J., Jensen, L., Hawkins, M. & Smith, E. 2020 Bull. AAS 235, 175.18 (2020AAS ...23527528L).

Margalit, B. & Metzger, B. D. 2018 ApJ 868, L4 (arXiv:1808.09969).

Mckinnon, R., Michilli, D., Masui, K. et al. 2021 ApJ 920, 138 (arXiv:2017.03491).

Michilli, D., Masui, K. W., Mckinnon, R. et al. 2021 ApJ 910, 147 (arXiv:2010.06748).

Niu, C.-H., Aggarwal, K., Li, D. et al. 2021 (arXiv:2110.07418).

Piro, A. L. & Gaensler, B. M. 2018 ApJ 861, 150 (arXiv:1804.01104).

Rajwade, K. M., Mickaliger, M. B., Stappers, B. W. et al. 2020 MNRAS 495, 3551 (arXiv:2003.03596).

Trotter, A. S., Reichart, D. E., Egger, R. E. et al. 2018 MNRAS 469, 1299.

Zhang, Y. G., Gajjar, V., Foster, G., Siemion, A., Cordes, J., Law, C. & Wang, Y. 2018 ApJ 866, 149 (arXiv:1809.03043).

APPENDIX A: THERMALLY SUPPORTED CLOUDS

If a homogeneous spherical cloud is supported by thermal pressure at a temperature \( T \) then there is an approximate relation among its mass \( M \), radius \( r \), atomic density \( n \), and temperature

\[
\frac{4\pi}{3} \frac{G m_n^2}{2r} \approx \frac{G M m_n}{2r} \approx k_B T,
\]

where we approximate the mean mass per particle as \( m_n \). This is consistent with the rapid variations of DM shown in ED Fig. 8 of Niu et al. (2021), so the hypothesis that the local contribution to the DM of FRB 190520B is produced by a pressure-supported interstellar cloud can be definitively rejected.
If the cloud were supported by turbulent motion rather than by thermal pressure, its lifetime would be short, either because these motions would disrupt it or because they would thermalize. The gas in our Galaxy is mostly supported by organized rotation, rather than either thermal pressure or turbulence, yet no line of sight other than to the Galactic center has a DM within an order of magnitude of that of the near-source contribution to the DM of FRB 190520B.