The Environment of FRB 121102 and Relation to SGR/PSR J1745-2900

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ABSTRACT
Variations of the dispersion (DM) and rotation (RM) measures of FRB 121102 indicate magnetic fields ∼ 3–17 mG in the dispersing plasma. The electron density may be ∼ 10^4 cm^{-3}. The observed time scales ∼ 1 year constrain the size of the plasma cloud. Increasing DM excludes simple models involving an expanding supernova remnant, and the non-zero RM excludes spherical symmetry. The varying DM and RM may be attributable to the motion of plasma into or out of the line of sight to or changing electron density within slower-moving plasma. The extraordinarily large non-zero RM excludes spherical symmetry. The varying DM and RM may be attributable to the motion of plasma size of the plasma cloud. Increasing DM excludes simple models involving an expanding supernova remnant, and the electron density may be ∼ in the dispersing plasma. The parallel component of magnetic field along the line of sight is related to the RM and DM:

\[ \langle B_\parallel \rangle_{n_e} = 1.23 \frac{\Delta RM}{\Delta DM} \mu G, \]

where the RM is in units of radians/m^2, the DM is in units of pc/cm^3 and the subscript \( n_e \) indicates this is the electron density-weighted average of the parallel (to the line of sight) component of magnetic field. In a homogeneous medium \( \langle B_\parallel \rangle_{n_e} \) equals a single value \( B_\parallel \).

The fact that the RM is an integral of the product \( B_\parallel n_e \) implies that it is dominated by the densest and most strongly magnetized regions, even if they make only a small contribution to the DM; the RM is quadratic in parameters that are likely correlated, while the DM is linear. In order to determine the magnitude of the magnetic field it is necessary to identify those regions’ contributions to the DM because most of the DM is likely contributed by long paths in low density interstellar and intergalactic plasmas that contribute negligibly to the RM. Only then can Eq. 1 be used to estimate \( \langle B_\parallel \rangle_{n_e} \). Unfortunately, for most FRB it is not possible to separate any contribution of a dense region to the DM from that of the interstellar (in both galaxies) and intergalactic media.

FRB 121102 is an exception. Not only is its RM extraordinarily large and rapidly varying, but it is the only FRB whose DM is known to change (Hilmarsson et al. 2020), increasing by about 2.5 pc/cm^3 in two years of accurate measurements. This change may be attributed to a compact dense region that is also the source of most of the (also varying) RM. It is then possible to estimate the magnitude of \( B_\parallel \) in this region.

In the simplest possible model this dense region is homogeneous, is the source of the entire RM and the RM and DM vary in proportion. If correct, this would also permit estimating this region’s contribution to the DM. A possible physical realization would be the intrusion into, or the withdrawal from, the line of sight of a homogeneous (in density and magnetic field) wedge of plasma, or a change in its ionization state. Then Eq. 1 becomes (Katz 2018)

\[ |\langle B_\parallel \rangle_{n_e}| = 1.23 \frac{|\Delta RM|}{|\Delta DM|} \mu G. \]

Key words: radio continuum, transients: fast radio bursts

1 INTRODUCTION
Wang et al. (2020) recently reviewed the magnetoionic environments of Fast Radio Bursts (FRB). The dispersion measures (DM) and rotation measures (RM) of most FRB have shown no detectable changes and are consistent with paths through the intergalactic medium and the interstellar media of our Galaxy and a host galaxy (whose properties are necessarily very uncertain). There is one striking exception, FRB 121102, whose RM has extraordinary values ∼ 10^4 mG, decreased by ≈ 30% during about three years of observations, and whose DM increased by about 2.5 pc/cm^3 (Hilmarsson et al. 2020). From these data it is possible to estimate the magnetic field and electron density in the dense, strongly magnetized, region in which the RM and a varying part of the DM are produced. No other FRB has such a high RM, but otherwise the phenomenology of FRB 121102 is not extraordinary.

The magnetoionic environment of SGR/PSR J1745−2900 may be similar; its RM is also large and rapidly varying, although no change in its DM has been reported. These two objects may be related, making SGR/PSR J1745−2900 a candidate FRB source.

2 MAGNETIC FIELDS
The parallel component of magnetic field along the line of sight is related to the RM and DM:

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The fact that the RM is an integral of the product \( B_\parallel n_e \) implies that it is dominated by the densest and most strongly magnetized regions, even if they make only a small contribution to the DM; the RM is quadratic in parameters that are likely correlated, while the DM is linear. In order to determine the magnitude of the magnetic field it is necessary to identify those regions’ contributions to the DM because most of the DM is likely contributed by long paths in low density interstellar and intergalactic plasmas that contribute negligibly to the RM. Only then can Eq. 1 be used to estimate \( \langle B_\parallel \rangle_{n_e} \). Unfortunately, for most FRB it is not possible to separate any contribution of a dense region to the DM from that of the interstellar (in both galaxies) and intergalactic media.

FRB 121102 is an exception. Not only is its RM extraordinarily large and rapidly varying, but it is the only FRB whose DM is known to change (Hilmarsson et al. 2020; Oosterom et al. 2020), increasing by about 2.5 pc/cm^3 in two years of accurate measurements. This change may be attributed to a compact dense region that is also the source of most of the (also varying) RM. It is then possible to estimate the magnitude of \( B_\parallel \) in this region.

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The observations of Hilmarsson et al. (2020) fall into three groups: I, comprising bursts 5 and 6 during MJD 58069–58075; II, comprising bursts 7–15 during MJD 58216–58348; and III, comprising bursts 16–20 during MJD 58678–58712. Between groups I and II $\Delta RM \approx -15000 \text{ m}^{-2}$ and $\Delta DM \approx 1.1 \text{ pc/cm}^3$; between groups II and III $\Delta RM \approx -4000 \text{ m}^{-2}$ and $\Delta DM \approx 1.6 \text{ pc/cm}^3$. Groups I and II are separated by about 160 days while groups II and III are separated by about 450 days.

Eq. 2 indicates $|B_\parallel| \sim 17 \text{ mG}$ for the transition between groups I and II and $|B_\parallel| \sim 3 \text{ mG}$ for the transition between groups II and III. Within this model, these estimates of the magnetic field do not depend on the temporal durations of the transitions. These fields are three or more orders of magnitude greater than typical estimated interstellar fields, and indicate that FRB 121102 is behind or immersed in an extraordinary region.

Assuming that the entire dense region $DM_{dr}$ varies when the RM varies,

$$|DM_{dr}| \sim \left| \frac{\text{RM}}{\Delta RM} \Delta DM \right| \sim 10 \text{ pc/cm}^3.$$  \hspace{1cm} (3)

This is only a rough estimate, but is consistent with the attribution of most of the DM to interstellar and intergalactic media, even though nearly all the RM must be attributed to the dense region.

3 NUMERICAL ESTIMATES

If the moving plasma that is the source of the changing DM and RM has a speed (that might be the phase speed of an ionization or recombination front rather than a material speed) $v$, then a change in properties over a time $\Delta t$ corresponds to a length scale $v\Delta t$. The characteristic electron density

$$n_e \sim \frac{\Delta DM}{v\Delta t}.$$  \hspace{1cm} (4)

Equating the magnetic stress to the gas pressure $P = 2n_e k_BT$ (assuming equal ion and electron temperatures), there is a characteristic temperature $T$:

$$2n_e k_BT = P = \frac{B_\parallel^2}{8\pi}.$$  \hspace{1cm} (5)

Combining Eqs. 2, 4 and 5,

$$k_BT = 6 \times 10^{-14} \left| \frac{\Delta RM}{\Delta DM} \right|^2 v_\gamma \Delta t \text{ eV},$$  \hspace{1cm} (6)

where RM and DM are in their usual units (radians/m$^2$ and pc/cm$^3$) and $v_\gamma \equiv v/(10^7 \text{ cm/s}).$

The inferred values of the parameters are shown in the Table. The assumptions, particularly that of pressure balance, are uncertain, but the estimated values of $k_BT$ have plausible orders of magnitude.

4 IMPLICATIONS

FRB 121102 is behind or immersed in an extraordinarily dense and strongly magnetized region, plausibly associated with the FRB source or with the event that made it. The inferred $n_e$ and $|\langle B_\parallel \rangle|n_e$ are much greater than those found in other interstellar plasmas. The data are consistent with any location of this region on the line of sight between the FRB source and the observer, but it is natural to associate it with the immediate environment of the source of FRB 121102.

The identification of FRB 200428 with SGR 1935+2154, associated with the supernova remnant (SNR) G57.2+0.8 (Kothes et al. 2018), suggests by analogy that the dense region on the line of sight to FRB 121102 may be a very young, dense and strongly magnetized remnant of the event that made its source, although the magnetoionc environment of SGR 1935+2154 is very different, with a modest RM plausibly attributed to the interstellar medium.

This explanation of the RM and DM of FRB 121102 is not entirely satisfactory. The expansion of a SNR generally produces a decreasing DM (Margalit & Metzger 2018; Piro & Gaensler 2018), in contradiction to the observed (Hilmarsson et al. 2020; Oostrum et al. 2020) increase, although increasing ionization could increase DM. More complex models (Zhao et al. 2020) may have more complex behavior. A spherically symmetric remnant cannot have a magnetic field at all, but a remnant might be approximately symmetric on large scales while being asymmetric (turbulent or otherwise structured) on smaller scales.

The changing DM and RM of FRB 121102 could be attributed to either a change in the magnetic field and density of a nebular filament on the line of sight or to the motion of such a filament across the line of sight. The observed reduction in $\text{RM}$ combined with an increase in DM implies the movement into the line of sight of comparatively dense plasma whose $B_\parallel$ is opposite to that dominant along the total line of sight, or an increase in the integrated column density of such a opposed region.

It is natural to compare the inferred parameters with those of the best-studied SNR, the Crab Nebula. Its magnetic field (Bietenholz & Kronberg 1990; Reynolds, Gaensler & Bocchino 2012) is less than that inferred for FRB 121102. However, direct comparison is inappropriate because the magnetic field of the Crab nebula is inferred for the low density synchrotron-radiating volume that must be a negligible contributor to both DM and RM; it is not possible to measure the field in the high density filaments directly. Further, both the Crab Nebula and its central neutron star differ from those that produce FRB 200428, and very plausibly other FRB. FRB 200428/SGR 1935+2154 has a spin rate about 100 times less than that of the Crab pulsar and a magnetic moment about 60 times greater. The age of FRB 121102 may be much less than that of the Crab Nebula and its pulsar; it

| Epoch | I–II | II–III |
|-------|------|-------|
| $\Delta RM$ (rad/m$^2$) | -15000 | -4000 |
| $\Delta DM$ (pc/cm$^3$) | +1.1 | +1.6 |
| $|B_\parallel|$ (mG) | 17 | 3 |
| $\Delta t$ (s) | $1.5 \times 10^7$ | $4 \times 10^7$ |
| $v$ (cm/s) | $1.5 \times 10^{14} v_\gamma$ | $4 \times 10^4 v_\gamma$ |
| $n_e$ (cm$^{-3}$) | $2 \times 10^7 v_\gamma^{-1}$ | $1 \times 10^9 v_\gamma^{-1}$ |
| $k_BT$ (eV) | $150 v_\gamma$ | $10 v_\gamma$ |

Table 1. The parameters of the plasma responsible for changes in DM and RM between Epochs I (bursts 5 and 6) and II (bursts 7–15) and between Epochs II and III (bursts 16–20) of Hilmarsson et al. (2020), estimated from Eqs. 2, 4 and 6.
must be at least eight years, but is otherwise empirically unconstrained.

5 DISCUSSION

It is remarkable that the RM and inferred \( \langle B_\parallel \rangle \) of FRB 121102 are orders of magnitude greater than those of any other FRB (Wang et al. 2020)\(^1\). If the sources of the DM are qualitatively similar in FRB 121102 and other FRB, as would be expected if they are gradually expanding and dissipating SNR with a continuous distribution of parameters (such as age, electron density and magnetic field), a smooth and continuous distribution of RM would be expected, perhaps a power law. This is inconsistent with the extraordinary \( \langle B_\parallel \rangle \) of FRB 121102; its environment differs qualitatively from those of other FRB, and its nature and origin may also differ.

The source of FRB 200428 shows an analogously anomalous distribution of burst strengths, with FRB 200428 orders of magnitude more intense than subsequent bursts from this source. This may be explained by the collimation of radiation emitted by relativistic charges into a narrow beam that may jitter or wander in direction (Katz 2020). No such explanation is apparent for the distribution of RM among FRB sources.

Hilmarsson et al. (2020) compared the observed properties of FRB 121102 to the SNR models of Margalit & Metzger (2018) and Piro & Gaensler (2018), and suggested birthdates in the range 2000–2010. The rapid decay of RM (30% in three years), if interpreted as exponential decay, would also suggest a characteristic age of about 10 years. No trend in the rate and strengths of outbursts of FRB 121102, that might be expected to decay as a young source ages, has been qualitatively evident in eight years of observation, but insufficient data exist to bound any trends quantitatively. The increase in DM argues against a rapidly dissipating (and therefore very young) SNR. As discussed in the Appendix, characteristic time scales of variation are only lower bounds on actual ages.

If a repeating FRB had a measured period and period derivative, these would constrain its age, although the possibility of a neutron star born recently with a long spin-down age could not be excluded—spindown age is only an upper bound on the actual age. Because FRB are episodic emitters, a birth date could only be established statistically from its absence in surveys prior to some date; CHIME/FRB might make this possible.

The only other astronomical objects with such extraordinarily large (and rapidly varying) RM are PSR J1745–2900 and the Galactic center black hole Sgr A*. This PSR has a projected separation from Sgr A* of only 0.1 pc, so the line of sight to PSR J1945–2900 passes through the region filled with plasma accreting onto the massive black hole. It is unsurprising that this region has unique properties, and Katz (2019) suggested that FRB are emitted by jets produced by intermediate mass black holes. That cannot explain FRB 200428, known to be emitted by a SGR (and that has an unremarkable RM, plausibly attributed to interstellar plasma), but is consistent with the hypothesis that there are at least two, qualitatively different, kinds of objects that produce FRB whose phenomenologies are not obviously distinct.

The rapid variation of the RM of PSR J1745–2900 may be inexplicable by this mechanism. A characteristic time scale \( \sim 6 \text{ y} \) (10% change in 7 months) (Michilli, Seymour & Hessels 2018) at a projected distance from Sgr A* of 0.1 pc would suggest a velocity \( \sim 10^9 \text{ cm/s} \), about 30 times the escape or orbital velocity of the \( 4 \times 10^6 \text{ M}_\odot \) black hole in SGR A*. Possible resolutions of this problem include propagation through an unslowed supernova shell and varying refraction, in which the high velocity is not a material velocity but a displacement velocity of the propagation path as a result of refraction by slower moving material. Application of this hypothesis to FRB 121102 would not invalidate the extraordinary implied \( n_e \) and \( \langle B_\parallel \rangle \), but would emphasize that the parameter \( v \) is uncertain.

Only upper limits to \( \Delta \text{DM} \) of PSR J1745–2900 exist, so it is not possible to estimate \( \langle B_\parallel \rangle \). However, these upper limits are comparable to the measured \( \Delta \text{DM} \) of FRB 121102 and the \( \Delta \text{RM} \) are of the same order of magnitude, so \( \langle B_\parallel \rangle \sim 10^9 \text{ mG} \) is at least plausible. The electron densities then inferred for FRB 121102 and PSR J1745–2900 imply very short (\( \sim 10^9 \text{ s} \)), unless the temperature is very high) recombination times. This may suggest very young ages, but is also consistent with the presence of a strong ionizing ultraviolet flux.

If varying refraction explains the rapid variation of the RM of FRB 121102, we cannot be on a caustic. The converging rays of a caustic, while having the same optical path (foci occur at extrema of the optical paths), would traverse paths of differing \( B_\parallel \), averaging out their linear polarization.

Perhaps the large and rapidly varying RM of PSR J1745–2900 has nothing to do with its proximity to Sgr A* (a separation of 0.1 pc is very large compared to \( v \Delta t \) for likely \( v \), but rather is associated with its environment on scales \( \ll 0.1 \text{ pc} \). PSR J1745–2900 and FRB 121102 might be members of a distinct class of object characterized by the behavior of their RM. If so, then the FRB activity of FRB 121102 suggests that PSR J1745–2900 might also be a source of FRB, a speculation supported by the discovery that SGR 1935+2154 made FRB 200428.

APPENDIX

It has been suggested (Gott 1993) on the basis of a “Copernican Principle” (of much older origin) that if a phenomenon has been observed for a period \( t \), the probability that its lifetime is \( \geq T \) is \( O(t/T) \). This has been used to argue that the expected lifetime of humanity (estimated to be \( \sim 300,000 \) years old, depending on the definition of when our ancestors became human) is unlikely to be more than a few million years, that the expected lifetime of the present American con-

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\(^1\) Wang et al. (2020) use Eq. 1 rather than Eq. 2 to infer \( \langle B_\parallel \rangle \), leading to an underestimate when most of the RM but little of the DM are contributed by a dense strongly magnetized region. For FRB 121102, most of whose RM must be produced in such a region (because the evidence of other FRB shows that interstellar and intergalactic plasma contribute much less RM), Eq. 1 may underestimate \( \langle B_\parallel \rangle \) by a factor \( \sim (\Delta \text{RM}/\text{RM})(\text{DM}/\Delta \text{DM}) \sim 50 \). The error is much less if most of the RM is produced in low density Galactic and host galactic interstellar media, as it may be for other FRB.
stitutional government, established in 1788, is unlikely to be more than a few thousand years, etc.

This argument depends on an assumed uniform prior probability of discovery through the lifetime of the phenomenon. This can be shown to be wrong, at least in some applications. For example, the rapid variation of some AGN might suggest ages of no more than a few years, but we are confident, on the basis of the physics of black hole formation and accretion, that their ages are $10^6$–$10^{10}$ years. The variation of the RM of PSR J1745−2900 suggests an age $\approx 6$ y, but the absence of a neutrino signal in Kamiokande and other neutrino observatories from its formation implies an age $\geq 37$ y, and the properties of SNR G57.2+0.8 in which it is embedded indicate an age of thousands or tens of thousands of years (Kothes et al. 2018). Hence, while the rapid variation of the RM of FRB 121102 suggests a very young SNR, its age cannot be estimated on this basis alone.

**DATA AVAILABILITY**

This theoretical study did not obtain any new data.

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