The Astrophysical Consequences of Intervening Galaxy Gas on Fast Radio Bursts

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ABSTRACT

We adopt and analyze results on the incidence and physical properties of damped Lyα systems (DLAs) to predict the astrophysical impact of gas in galaxies on observations of Fast Radio Bursts (FRBs). Three DLA measures form the basis of this analysis: (i) the H I column density distribution, parameterized as a double power-law; (ii) the incidence of DLAs with redshift (derived here), \( \dot{\tau}_{\text{DLA}}(z) = A + B \arctan(z - C) \) with

\[
A = 0.236^{+0.016}_{-0.013}, \quad B = 0.168^{+0.010}_{-0.017}, \quad C = 2.87^{+0.17}_{-0.13};
\]

and (iii) the electron density, parameterized as a log-normal deviate with mean \( 10^{-2.8} \) cm\(^{-3} \) and dispersion 0.3 dex. Synthesizing these results, we estimate that the average rest-frame dispersion measure from the neutral medium of a single, intersecting galaxy is \( \text{DM}^{\text{NM}}_{\text{DLA}} = 0.25 \text{pc cm}^{-3} \). Analysis of Al\(^{iii} \) and C\(^{ii} \) absorption limits the putative warm ionized medium to contribute \( \text{DM}^{\text{NM}}_{\text{DLA}} < 20 \text{pc cm}^{-3} \). Given the low incidence of DLAs, we find that a population of FRBs at \( z = 2 \) will incur \( \text{DM}^{\text{NM}}_{\text{DLA}}(z_{\text{FRB}} = 2) = 0.01 \text{pc cm}^{-3} \) on average, with a 99% c.l. upper bound of 0.22 pc cm\(^{-3} \). Assuming that turbulence of the ISM in external galaxies is qualitatively similar to our Galaxy, we estimate that the angular broadening of an FRB by intersecting galaxies is negligible (\( \theta_{\text{scatt}} < 0.1 \text{ mas} \)). The temporal broadening is also predicted to be small, \( \tau_{\text{DLA}} \approx 0.3 \text{ ms} \) for a \( z = 1 \) galaxy intersecting a \( z = 2 \) FRB for an observing frequency of \( v = 1 \text{ GHz} \). Even with \( v = 600 \text{ MHz} \), the fraction of sightlines broadened beyond 25 ms is only approximately 0.1%. We conclude that gas within the ISM of intervening galaxies has a minor effect on the detection of FRBs and their resultant DM distributions. Download the repository at https://github.com/FRBs/FRB to repeat and extend the calculations presented here.

Key words: (galaxies:) intergalactic medium – galaxies: ISM

1 INTRODUCTION

The discovery of the ‘repeating’ Fast Radio Burst (Spitler et al. 2016, FRB) and subsequent follow-up observations at the Very Large Array (Chatterjee et al. 2017) have lead to the confirmation that at least some FRB events have an extragalactic origin (Tendulkar et al. 2017). In turn, the large Dispersion Measure (DM) that essentially defines an FRB offers one the opportunity to study the integrated electron column density along individual sightlines through the universe. New and upcoming surveys – e.g. CHIME (Bandura et al. 2014), ASKAP (Bannister et al. 2017), APERTIF, REALFAST (Bower et al. 2016) – will yield a terrific set of observations to measure baryons in the \( z < 1 \) universe and possibly beyond, complementing decades of work in the far-UV (e.g. Dave & Tripp 2001; Chen et al. 2005; Tejos et al. 2014).

For a source at great distance, e.g. \( z \sim 1 \) or approximately 2.4 Gpc, one expects a significant DM from the diffuse, highly-ionized intergalactic medium (Inoue 2004, IGM). In quasar absorption line (QAL) parlance, this plasma is referred to as the Lyα forest. Gas in the dark matter halos of galaxies will also contribute and may even dominate (McQuinn 2014, ; Prochaska & Zheng 2017, in prep.). This gas in QAL research is referred to as the circumgalactic medium (CGM), which one frequently associates to the optically thick Lyman limit systems (LLSs; e.g. Fumagalli et al. 2011; Ribaudo et al. 2011; Hafen et al. 2016). Most rarely, an FRB sightline may penetrate the ISM of a galaxy akin to our own. If the neutral hydrogen column density \( N_{\text{HI}} \) equals or exceeds \( 2 \times 10^{20} \text{ cm}^{-2} \), the QAL community refers to the absorption as a damped Lyα (DLA) system (Wolfe et al. 1986, 2005). In the far-UV, a DLA system shows a quantum mechanically ‘damped’ Lyα line with equivalent width \( W_{1390} > 10 \text{ Å} \). In addition to contributing to the DM value of an FRB, the free electrons in DLAs – if turbulent – will

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scatter the radio pulse (Macquart & Koay 2013). Turbulent scattering broadens both the angular size of the source and the intrinsic duration of the event.

The DLA contribution to DM is distinct from other intervening gas because: (1) DLAs arise in collapsed (i.e. highly non-linear) structures; and (2) they trace a predominantly neutral gas with ionization fraction $x \equiv n_e/n_H \ll 1$. We emphasize that the analysis performed here considers primarily the neutral gas of DLAs, i.e. the warm and cold neutral media (WNM/CNM) of external galaxies. We also consider a putative warm ionized medium (WIM) surrounding DLAs. We explicitly ignore, however, gas in the dark matter halos hosting DLAs which is believed to be traced by high ions like C$^{+3}$ and Si$^{+3}$ (Wolfe & Prochaska 2000a,b; Maller et al. 2003; Fox et al. 2007; Prochaska et al. 2008a).

The astrophysical impact of galactic halos on FRBs will be treated in a companion paper (Prochaska & Zheng 2017, in prep.; see also McQuinn 2014). We recognize that the DLA criterion is somewhat arbitrary and gas with modestly lower column densities (the so-called super Lyman limit systems or sub-DLAs) may be treated in a companion paper (Prochaska & Neeleman 2013) as well. Including such systems explicitly in the companion paper. We note that the code provided with this paper can easily be modified to include such material within the framework developed here.

It has been proposed that intervening galaxies will essentially ‘extinguish’ the FRB signal by broadening the pulse duration to a non-detectable signal (Macquart & Koay 2013; McQuinn 2014). Analogous to dust obscuring UV-bright quasars to bias observed sightlines against a subset of DLAs (Ostriker & Heisler 1984; Fall & Pei 1993), it is possible that the observed FRB population will not occur along sightlines that intersect galaxies. In turn, this may bias the observed DM distribution and alter the observed redshift distribution of FRBs. A precise characterization of these effects is therefore critical to inferring the intrinsic nature of FRBs and for utilizing the population to constrain cosmological quantities (e.g. Gaensler et al. 2008). In this paper, we analyze the latest results from DLA surveys to empirically estimate the impact of DLAs on current and future FRB studies. This includes statistics on the incidence of DLA absorption $f_{DLA}(z)$, the frequency distribution of $N_H$, aka $f(N_{HI}, z)$, and constraints on the electron volume density $n_e$. Throughout, we adopt the Planck 2015 cosmology (Planck Collaboration et al. 2016) encoded in the astropy (v1.3). All of the calculations presented here may be reproduced and extended using codes in this repository: https://github.com/FRBs/FRBs.

2 THE DISPERSION MEASURE OF DLAS

As emphasized above, gas in intervening galaxies will contribute to the DM of FRBs for those sightlines that intersect any such galaxies. On the reasonable ansatz that all galaxies with a non-negligible DM will also have an $N_H$ value satisfying the DLA criterion, we may use statistics and measured properties of the latter to predict the effects of the former. This forms the basis of our methodology.

We may construct an empirical estimate for the average DM value from the neutral medium in DLAs for a FRB at redshift $z_{FRB}$, $\overline{DM}_{DLA}(z_{FRB})$, as follows. Formally, we have,

$$\overline{DM}_{DLA}(z_{FRB}) = \int \int f(N_{HI} , z) N_{HI} x_{DLA}(N_{HI})(1+z)^{-1} dN_{HI} dz ,$$

where we have defined $x_{DLA} \equiv n_e/n_H$ with $n_H \approx n_{HI}$ for the predominantly neutral DLAs. One recognizes $f(N_{HI}, z)$ as the H I frequency distribution, i.e. $f(N_{HI}, z) dN_{HI} dz$ is the estimated number of DLAs in $N_{HI}$ and redshift intervals.

Thus far, DLA surveys have not revealed a significant evolution in the shape of $f(N_{HI}, z)$ with redshift. Therefore, we will assume that the function describing $f(N_{HI}, z)$ is separable (see also Inoue et al. 2014), i.e.

$$f(N_{HI}, z) = h(N_{HI}) f(z) .$$

For the first term, we adopt the double power-law derived by Prochaska et al. (2005) from their analysis of the SDSS-DR5:

$$h(N_{HI}) = K \left( \frac{N}{N_d} \right)^{\beta} \quad \text{where} \quad \beta = \left\{ \begin{array}{ll} \alpha_1 : N < N_d; \\
\alpha_2 : N \geq N_d; \end{array} \right.$$  \hspace{1cm} (3)

with $N_d = 10^{21.551} \text{cm}^{-2}$, $\alpha_3 = -2.055$, and $\alpha_4 = -6$. While there have been more recent and larger surveys of DLAs from BOSS (e.g. Noterdaeme et al. 2012; Bird et al. 2017), most have not provided functional fits to their $f(N_{HI}, z)$-analysis.

Furthermore, our own efforts with deep-learning techniques raises concerns on several of the reported results Parks et al. (2017). In any case, as progress on DLA surveys continues, we will ingest and update the accompanying repository and the results on FRBs are relatively insensitive to the precise form of $h(N_{HI})$.

To constrain $f(z)$, we perform a new calculation of the incidence of DLAs:

$$f_{DLA}(z) = \int \int f(N_{HI}, z) dN_{HI} = j(z) \int h(N_{HI}) dN_{HI} .$$ \hspace{1cm} (4)

In the following, we set the normalization $K$ of $h(N_{HI})$ such that $f_{DLA}(z) = j(z)$, i.e. the integral over $h(N_{HI})$ is unity. Many DLA surveys have been analyzed to assess $f_{DLA}(z)$ across cosmic time (e.g. Wolfe et al. 1995; Storrie-Lombardi & Wolfe 2000; Prochaska et al. 2005; Rao et al. 2017). The standard approach is to first evaluate the search path for DLAs, a.k.a. $g(z)$ or the number of independent quasar sightlines surveyed for DLA absorption at a given redshift. A good estimator for the incidence in a finite redshift interval $\Delta z$ at redshift $z$ is

$$f_{DLA}(z) = N_{DLA}/\Sigma_{z}$$ \hspace{1cm} (5)

1. Note that this differs from the full population of QALs, e.g. Worseck & Prochaska (2011).

2. An analysis of the complete SDSS survey yields $f(N_{HI}, z)$ with a fully consistent shape as the one adopted here (Noterdaeme et al. 2009).

3. https://github.com/FRBs/FRBs
with \(N_{\text{DLA}}\) the number of DLAs detected in \(\Delta z\), and the sum on \(g(z)\) is performed over the same interval.

The left panel of Figure 1 summarizes the redshift path analyzed by the DLA surveys adopted here: a blind search for DLAs at \(z < 2\) in Hubble Space Telescope UV spectroscopy, HST-DLA (Neelam et al. 2016); a survey of quasars from the SDSS data release 5, SDSS-DR5 (Prochaska & Wolfe 2009); a survey of 100 quasars at \(z = 3–4\) observed with the X-Shooter spectrograph, XQ-100 (López et al. 2016; Sánchez-Ramírez et al. 2016); a survey for \(z > 3.5\) DLAs using the Gemini GMOS spectrometers, GGG-DLA (Worseck et al. 2014; Crighton et al. 2015). The cumulative distribution of DLAs detected, \(N_{\text{DLA}}\), is shown in the right panel. One point is obvious from the figure: despite the survey of many hundreds of quasars at \(z < 1\) with HST, only a handful of DLAs were detected\(^4\). This primarily follows from cosmological expansion, i.e., one predicts that the observed incidence decreases as \((1+z)^2\) for an unevolving population of absorbers per comoving volume in a \(\Lambda\)-dominated universe.

From the data in Figure 1, we have used the estimator in Equation 5 to calculate \(\ell_{\text{DLA}}(z)\) in select bins (Figure 2). Here we derive uncertainties assuming Poisson statistics. It is apparent that \(\ell_{\text{DLA}}(z)\) increases with redshift from low values at \(z < 1\). The figure also show an estimate for \(\ell(z)\) at \(z = 0\) based on 21 cm observations where we have combined the values reported by Zwaan et al. (2005) and Braun (2012): 
\[
\ell(z)_{21\text{cm}} = 0.035 \pm 0.01
\]

Most previous analyses of \(\ell_{\text{DLA}}(z)\) have assumed it follows the functional form \((1+z)^\gamma\). This is physically motivated by cosmological expansion, but Prochaska et al. (2008b) emphasized that the evolution in \(\ell_{\text{DLA}}(z)\) at \(z \approx 2–3\) is not well described by such a power-law. Lacking a proper physical model for \(\ell_{\text{DLA}}(z)\), we take an empirically driven approach and seek a functional form that describes the data well at all redshifts and with the fewest number of parameters. After some experimentation, we settled on a model,

\[
\ell_{\text{DLA}}(z) = A + B \arctan(z - C)
\]

which captures an apparent inflection in \(\ell_{\text{DLA}}(z)\) at the highest redshifts studied (Crighton et al. 2015). We performed a standard maximum likelihood analysis to find the best values for \(A, B\) and \(C\) as shown in Figure 2 and listed in Table 1. Errors on these parameters were estimated using standard bootstrap techniques. All of the data and our new \(\ell_{\text{DLA}}(z)\) result are ingested in the \texttt{pyigm} package.

With \(\ell_{\text{DLA}}(z)\) well-fitted, we may calculate the average number of DLAs intervening a source at redshift \(z_{\text{FRB}}\) as:

\[
\bar{n}_{\text{DLA}}(z_{\text{FRB}}) = \int_0^{z_{\text{FRB}}} \ell_{\text{DLA}}(z) \, dz = \frac{\zeta_{\text{FRB}}}{A} C \arctan C + \frac{B}{A} \ln(\mu^2 + 1)/2 - C \arctan C + \ln(C^2 + 1)/2
\]

with \(\mu = C - C_{\text{FRB}}\). For a single sightline to an FRB, the uncertainty in \(\bar{n}_{\text{DLA}}(z_{\text{FRB}})\) is dominated by Poisson sampling with \(\sigma^2(\bar{n}_{\text{DLA}}) = \bar{n}_{\text{DLA}}\). For a population of FRBs, the uncertainty is dominated by errors in our estimation of \(\ell_{\text{DLA}}(z)\). Figure 3 shows \(\bar{n}_{\text{DLA}}(z_{\text{FRB}})\) versus redshift, where one recovers a value of 0.04 for \(z_{\text{FRB}} = 1\) and one notes \(\bar{n}_{\text{DLA}}(z_{\text{FRB}})\) remains less than unity until nearly \(z_{\text{FRB}} = 5\). This relatively low incidence strictly limits the potential impact of intervening galaxies on FRBs.

\(^4\) We do not include here the DLA surveys of Rao & Turnshek who targeted strong Mg ii absorbers to detect DLAs (Rao et al. 2006, 2017).

\(^5\) https://github.com/pyigm/pyigm
Figure 3. Average number of DLAs $\bar{n}_{DLA}(z_{FRB})$ intersected by a sightline to a source at redshift $z_{FRB}$. For $z_{FRB} = 1$, we estimate $\bar{n}_{DLA}(z_{FRB}) < 0.05$ and the value remains less than unity until $z_{FRB} = 5$. For a population of events at a given redshift, the number of DLAs observed will be Poisson distributed with mean and variance of $\bar{n}_{DLA}(z_{FRB})$. This relatively low incidence strictly limits the potential impact of intervening galaxies on FRBs.

Owing to the large $^{1}\text{HI}$ column densities that define DLAs, the gas is (extremely) optically thick to $^{1}\text{HI}$ ionizing radiation and one expects DLAs to be predominantly neutral gas. This has been demonstrated theoretically and empirically (e.g. Viegas 1995; Vladilo et al. 2001), although there are notable, individual counter-examples (e.g. Prochaska et al. 2002). A direct assessment of the neutral fraction of DLAs (or any QAL) is challenged by the fact that the commonly observed resonance lines are insensitive to the physical conditions of density, temperature, etc. Therefore, direct measurements of $^{2}\text{HLA}$ are difficult to obtain.

A notable exception is to assess the physical conditions within DLAs by analyzing absorption from the excited states of $^{3}\text{C}$ and $^{3}\text{Si}$ (Howk et al. 2005). The most comprehensive study to date was by Neeleman et al. (2015) who used an MCMC analysis to derive estimates of the electron and hydrogen number densities $n_e$ and $n_{^1\text{H}}$ for $\approx 80$ DLAs at $z \approx 2 - 5$. Figure 4 summarizes the results versus the $^{1}\text{HI}$ column density for the 50 systems with $^{3}\text{C}^{*}$ detected. There is a small trend of decreasing ionization fraction with $n_{^1\text{H}}$ that we parameterize as

$$\log x_{DLA} = \log \frac{n_e}{n_{^1\text{H}}} = -2.881 - 0.352 \left(\log N_{^1\text{H}} - 20.3\right) . \tag{8}$$

We proceed by assuming a 0.5 dex uncertainty in $n_e$ for any given DLA.

We now have all the ingredients necessary to offer an estimate for the average DM for a sightline intersecting one galaxy,

$$D_{MNRAS}^{DM, \text{DLA}} = \frac{\int_{10^{20.3}}^{\infty} h(N_{^1\text{H}})N_{^1\text{H}} x_{DLA} dN_{^1\text{H}}}{\int_{10^{20.3}}^{\infty} h(N_{^1\text{H}}) dN_{^1\text{H}}} \approx < N_{^1\text{H}} > x_{DLA}(< N_{^1\text{H}} >) = 0.25 \bar{n}_{DLA}(z_{FRB}) \left[\frac{N_{^1\text{H}}}{N_{^1\text{H}}(z_{FRB})}\right]^{3} = (1 + \bar{z})^{-1} \tag{9}$$

This is substantially smaller than the lowest values measured for sightlines intersecting our own ISM (Gaensler et al. 2008, $\approx 25pc cm^{-3}$, from the Sun).

We restrict our analysis to $^{3}\text{C}^{*}$ detections because non-detections yield little constraint on the electron density. However, by restricting the $n_e/n_{^1\text{H}}$ assessment to DLAs with $^{3}\text{C}^{*}$ detections, we may be biased towards sightlines dominated by the CNM (Wolfe et al. 2003; Neeleman et al. 2015), and therefore lower ionization fractions. Indeed, models of a multi-phase ISM predict ionization fractions for the WNM phase of $\approx 0.1$ (e.g. Wolfe et al. 1995). We note, however, that DLAs without $^{3}\text{C}^{*}$ detections have systematically lower $N_{^1\text{H}}$ values. For the $D_{MNRAS}^{DM, \text{DLA}}$ measurement, the ionization fraction gets weighted by $N_{^1\text{H}}$ and the bias resulting from omitting these systems is thereby at least partially offset. An additional bias toward sightlines dominated by the CNM could have been introduced from the selection criteria adopted by Neeleman et al. (2015). However, even if we assume that a majority of the gas arises in the WNM, as is indicated by 21cm observations of radio-loud quasars with intervening DLAs (Kanekar & Chengalur 2003; Kanekar et al. 2014), the primary conclusions of the paper remain unchanged.

Because the shape of $f(N_{^1\text{H}}, z)$ is taken to be invariant with redshift, the $dN_{^1\text{H}}$ integral in Equation 9 may be evaluated independently to derive an approximate expression for the average contribution for a population of FRBs at $z_{FRB}$:

$$\bar{z}$$ the average redshift of intervening galaxies. Evaluating Equation 10 at $z_{FRB} = 1$, we estimate $D_{MNRAS}^{DM, \text{DLA}}(z_{FRB} = 1)$.
1) \approx 0.0065 \text{ pc cm}^{-3}. To generate a more accurate evaluation of $\overline{DM}_{\text{DLA}}(z_{\text{FRB}})$, we have performed a Monte Carlo simulation of $10^6$ sightlines to FRBs over a series of $z_{\text{FRB}}$ values. For each realization, we draw the number and redshifts of DLAs on the sightline according to $f_{\text{DLA}}(z)$, (allowing for Poisson variance in $n_{\text{DLA}}(z_{\text{FRB}}))$, assign random $N_{\text{HI}}$ values drawn from $h(N_{\text{HI}})$, evaluate $x_{\text{DLA}}$, and calculate the DM value. The results are shown in Figure 5, and we find small values at all $z_{\text{FRB}}$. We also show the 68% and 99% intervals and find that \approx 1% of FRB sightlines originating at $z_{\text{FRB}} = 5$ will experience a contribution of \approx 0.2 \text{ pc cm}^{-3} from the neutral ISM of intervening galaxies.

As emphasized above, in our Galaxy the smallest DM values measured from our position at the Sun are approximately 25 pc cm\(^{-3}\). It is accepted that a warm ionized medium (WIM), which also generates nearly ubiquitous H\(_\alpha\) emission across the sky (e.g. Reynolds et al. 1998), is responsible for this ‘floor’ to the Galactic DM (e.g. Cordes & Lazio 2003). Several studies have used the observed DM distribution of pulsars with Galactic latitude and distance to model the density, filling factor, and distribution with scale height of electrons in the WIM (Gaensler et al. 2008; Berkhuijsen & Fletcher 2008).

The Galactic WIM is believed to be primarily generated by photons from O stars that have ‘leaked’ through their H\(_\text{II}\) regions (Haffner et al. 2009). Many external galaxies at $z \sim 0$ also exhibit a WIM component typically referred to as diffuse ionized gas or DIG (e.g. Rand 1997). At high $z$, the presence and nature of the WIM in galaxies has not yet been established. One notes that the average star formation rate in high-$z$ galaxies is higher which could accentuate a WIM, but the ISM may also be denser and less porous. Separately, the extragalactic UV background, which is more intense at high $z$, may ionize the outer ISM of galaxies to produce a WIM component.

In analogy with the Galactic ISM, it is possible that DLAs are also enveloped in layers of predominantly ionized gas, i.e. a WIM component\(^6\). Indeed, Howk & Sembach (1999) first emphasized that the frequent detection of Al\(^{++}\) in DLAs suggests a putative warm ionized medium, noting that Al\(_{III}\) absorption in our Galaxy traces its underlying electron distribution (Savage et al. 1990). Furthermore, the Al\(_{III}\) absorption in DLAs more frequently traces the low-ion transitions instead of the more highly ionized gas revealed by e.g. C\(_{IV}\) (Wolfe & Prochaska 2000a). On the other hand, one may ionize a non-negligible fraction of Al\(^+\) to Al\(^{++}\) via hard radiation from local sources or the EUVB without significantly ionizing hydrogen because of the large cross-section of Al\(^+\) to high-energy photons (Sofia & Jenkins 1998; Prochaska et al. 2002). In any event, we estimate an additional contribution to DM from DLAs based on their $N(\text{Al}^{++})$ measurements. This estimate will also include any contribution from a WNM component that was not captured by our treatment above.

Specifically, we assume that Al\(^{++}\) traces a predominantly ionized gas ($x_{\text{DLA}} \approx 1$) and that it is the dominant ionization state of Al in this plasma. It follows that,

$$N_\epsilon = N(\text{Al}^{++}) - N(\text{Al}) + 12. - \log(Z/Z_\odot), \quad (11)$$

with $N(\text{Al})$ the number abundance of Al in the Sun (6.43; Asplund et al. 2009) and $Z/Z_\odot$ the metallicity of the DLA relative to solar. Figure 6 shows $DM_{\text{AIM}}$ values derived with Equation 11 versus $N_{\text{HI}}$ using the HIRES sample of Neeleman et al. (2013); statistical uncertainties of approximately 0.2 dex are dominated by the error in $Z/Z_\odot$. Even with the somewhat extreme assumptions encoded by Equation 11, we derive a median $DM_{\text{AIM}}$ value of less than 20 pc cm\(^{-3}\). One also notes that the highest $DM_{\text{AIM}}$ values are associated primarily with high $N_{\text{HI}}$ DLAs suggesting that this gas arises in the WNM/CNM. Altogether, we constrain $DM_{\text{WIM}}$ to be less than 20 pc cm\(^{-3}\) and likely less than 10 pc cm\(^{-3}\). This upper limit is also consistent with the many non-detections of C\(_{IV}\) absorption in DLAs (Wolfe et al. 2003).

### 3 SCATTERING

The radio emission from a distant, compact source that intersects a DLA may be scattered by electron density inhomogeneities in the gas. The effects include an angular broadening of the source $\theta_{\text{scat}}$ and temporal broadening $\tau_{\text{scat}}$. Both exhibit a frequency dependence. The scattering processes has been studied extensively for sightlines through the ISM to pulsars in our Galaxy (Taylor & Cordes 1993), and the formalism has been developed for gas intersecting FRBs by (Macquart & Koay 2013; ; hereafter M13). We do not repeat

\[^6\] Note again that we distinguish here from gas in the dark matter halo presumed to contain DLAs. This CGM component is discussed in a separate manuscript (Prochaska & Zheng 2017, in prep.; see also McQuinn 2014).
their complete derivation here but present key expressions, treating angular and temporal broadening separately.

3.1 Angular Broadening

The angular broadening of an image by a point source has radius (half-width at half-maximum),

\[ \theta_{\text{scatt}} = f \frac{D_{LS}}{D_S k r_{\text{diff}}} , \]  

with \( f \) a factor of order unity, \( D_{LS} \) and \( D_S \) the angular diameters from the source to the phase plane and to the source respectively, \( k \equiv 2\pi/\lambda_0 \) with \( \lambda_0 \) the wavelength in the observer frame, and \( r_{\text{diff}} \) parameterizes the phase structure function in the form,

\[ D_{\phi}(r) = \left( \frac{r}{r_{\text{diff}}} \right)^{\beta-2} , \]  

under the assumption of a power-law spectrum of density inhomogeneities. M13 provide expressions for \( r_{\text{diff}} \) (see their Equation 7a) in two regimes: (i) \( r_{\text{diff}} < \ell_0 \), with \( \ell_0 \) the inner scale of the inhomogeneities and; (ii) \( r_{\text{diff}} \gg \ell_0 \). In the following\(^7\), we take \( \ell_0 = 1 \) AU and adopt a Kolmogorov spectrum with \( \beta = 11/3 \).

\(^7\) The software accompanying this paper allows for alternate choices for \( \ell_0 \) and \( \beta \).

Figure 6. The points track estimates of DM for a putative WIM component in DLAs by adopting Equation 11 and the Al\(^{3+}\) column density measurements and metallicities reported for \( z \sim 2 \) (mention pyigm). For sightlines intersecting fewer than \( 10^3 \) hydrogen atoms, we infer \( \text{DM}_{\text{AlIII}} < 30 \text{pc cm}^{-3} \). The positive correlation between \( \text{DM}_{\text{AlIII}} \) and \( N_{\text{HI}} \) implies that a significant fraction of the observed Al\(^{3+}\) absorption arises in neutral gas and, therefore, that \( \text{DM}_{\text{AlIII}} \) likely overestimates the true contribution to DM from any WIM component.

In the M13 formalism, \( r_{\text{diff}} \) is a function of the Scattering Measure (SM) which is an integral over the squared amplitude of density fluctuations along the sightline, \( C_N^2(s) \). For extragalactic calculations, one typically introduces an effective Scattering Measure:

\[ \text{SM}_{\text{eff}} = \int \frac{C_N^2(s)}{(1+z)^2} ds \]  

Following Equation 29 of M13, we estimate

\[ \text{SM}_{\text{eff}} \approx 5.6 \times 10^{16} \text{ m}^{-17/3} \left( \frac{n_e}{10^{-2} \text{ cm}^{-3}} \right)^2 \left( \frac{L_0}{10^{-3} \text{ pc}} \right)^{-2/3} \left( \frac{\Delta L}{1 \text{ kpc}} \right) \left( \frac{2}{1 + z_{\text{DLA}}} \right) \]  

with \( \Delta L \) our adopted ‘size’ for a DLA. With the \( \text{SM}_{\text{eff}} \) given above, we estimate \( r_{\text{diff}} = 2.2 \times 10^3 \text{ m} \) for \( \Delta L = 30 \text{ cm} \). This implies an essentially negligible angular broadening of \( \approx 0.02 \text{ mas} \) for any source far behind the DLA. We conclude that the ISM of galaxies intervening FRBs will insignificantly broaden the angular size of any background source.

3.2 Temporal Broadening

The other significant effect from turbulent scattering is that multi-path propagation through the medium leads to temporal broadening of the burst. This effect may yield an FRB with much longer observed duration than the intrinsic event and even preclude detection by current and planned experiments (e.g. Chawla et al. 2017).

Following M13, the temporal smearing may be related to angular scattering,

\[ \tau_{\text{scatt}} = \frac{D_L D_S g_{\text{scatt}}^2}{c D_{LS} (1+z_{\text{DLA}})^2} \]  

The \( g_{\text{scatt}}^2 \) term gives a very steep frequency dependence, i.e.
Fraction of FRBs with \( \tau_{\text{scatt}} \propto \nu^{-\gamma} \) with \( \gamma \approx 4-5 \), and has an electron density dependence of \( \tau_{\text{scatt}} \propto n_e^2 \). This is illustrated in Figure 7 for a fiducial DLA with electron densities ranging about our adopted, characteristic value. For \( n_e < 10^{-3} \text{ cm}^{-3} \), \( \tau_{\text{DLA}} < 1 \text{ ms} \) even for \( \nu = 400 \text{ MHz} \) and the effects on the FRB population are likely negligible. Larger \( n_e \) values, however, may have observational consequences. For \( n_e = 10^{-2} \text{ cm}^{-3} \) and \( \nu = 1 \text{ GHz} \), \( \tau_{\text{scatt}} \) exceeds several ms which is comparable to the median width for the current set of observed FRBs (Petroff et al. 2016). Events with \( \tau_{\text{scatt}} > 5 \text{ ms} \) will have reduced signal-to-noise \((S/N \propto \tau_{\text{scatt}})\) and those exceeding 100 ms will not trigger most, current FRB search algorithms.

We further emphasize that \( \tau_{\text{scatt}} \) has an explicit \((1+z)^{-1}\) dependence and \( \theta_{\text{scatt}} \) has the same factor implying \( \tau_{\text{scatt}} \propto (1+z)^{-2} \). Given the incidence for DLAs remains small for \( z_{\text{L}} < 1 \), their impact on broadening of the FRB signal is small. From our analysis, we may estimate the fraction of FRB sightlines originating at redshift \( z_{\text{FRB}} \) that will be broadened by at least \( \tau_{\text{min}} \). We performed a Monte Carlo simulation of 10^7 sightlines for a series of \( \nu_{\text{FRB}} \) values, randomly inserting DLAs from a Poisson distribution with mean \( \overline{N}_{\text{DLA}}(z_{\text{FRB}}) \).

Each DLA is then assigned a random \( N_H \) value drawn from \( h(N_H) \) to estimate \( \Delta \tau = N_H/\langle N_H \rangle \) with \( \langle N_H \rangle = 0.1 \text{ cm}^{-3} \), and a random electron density. For the latter, we have assumed a Gaussian distribution in \( \log n_e \) centered on \( \log(n_e/\text{cm}^{-3}) = -2.6 \) with a \((0.5 \text{ dex})^2\) variance. For sightlines with multiple DLAs, we add \( \tau_{\text{scatt}} \) in quadrature.

Figure 8 shows the results for several observed frequencies and \( \tau_{\text{min}} \) values. Experiments with \( \nu = 1 \text{ GHz} \) are predicted to have only \( \approx 0.1\% \) of their sightlines broadened beyond 5 ms. We conclude that the ISM of intervening galaxies has negligible impact on any experiment with \( \nu > 1 \text{ GHz} \) (e.g. REALFAST). For \( \nu = 600 \text{ MHz} \) (e.g. CHIME), the effects are modest but potentially impactful. Approximately 1% of the sightlines for FRBs at \( z_{\text{FRB}} > 1 \) are broadened by greater than 5 ms and \( \approx 10^{-4} \) have \( \tau_{\text{DLA}} > 100 \text{ ms} \). This implies a small but not entirely negligible impact on the population of FRBs discovered at low frequencies. Experiments at even lower frequencies (e.g. LOFAR) will be affected, if the ISM is as modeled here. One can, of course, invert the situation and place constraints on ISM properties by surveying FRBs at a range of frequency.

4 CONCLUDING REMARKS

In this manuscript, we have utilized surveys of DLAs to infer the astrophysical impacts of the ISM in intervening galaxies on FRB events. The principal conclusion is that intervening galaxies will contribute minimally to the integrated DM of an FRB. For a DLA at redshift \( z_{\text{DLA}} \), the average contribution from its neutral ISM is \( \Delta \text{DM} = 0.25 \text{ pc cm}^{-3} (1+z_{\text{DLA}})^{-1} \) as estimated from the H I column density and \( n_e/\langle n_e \rangle \) distribution functions. Given the low incidence of intervening galaxies, the average contribution along the sightline to an FRB is less than \( 10^{-5} \text{ pc cm}^{-3} \). From \( N(\text{Al}^{++}) \) measurements in DLAs, we estimate that the warm ionized component within these galaxies typically contributes \( \Delta \text{DM} = 0.2 \text{ pc cm}^{-3} \).

Similarly, the angular and temporal broadening of FRBs by the ISM of intervening galaxies is nearly negligible for all but the lowest frequency experiments.

While our results indicate that FRB analysis will typi-
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Table 1. \(N_{\text{HI}}\) MEASUREMENTS

| Measure         | Param. | Unit | Value 16th | 84th | 0.5th | 99.5th |
|-----------------|--------|------|------------|------|-------|--------|
| \(h(N_{\text{HI}})\) | \(N_d\) |      | 21.551     |      |       |        |
|                 | \(\alpha_1\) |      | -2.055     |      |       |        |
| \(f_{\text{DLA}(z)}\) | \(A\) |      | 0.236      | 0.214| 0.255 | 0.186  |
|                 | \(B\) |      | 0.168      | 0.150| 0.177 | 0.132  |
|                 | \(C\) |      | 2.869      | 2.717| 3.020 | 2.465  |
| \(\Delta M_{\text{DLA}}\) | pc cm\(^{-3}\) |      | 0.18       | 0.5 dex | 0.5 dex | 1.0 dex | 1.0 dex |
| \(\Delta M_{\text{NM}}\) | pc cm\(^{-3}\) |      | 0.004      | 0.000 | 0.000 | 0.000  |
| \(\tau_{\text{DLA}}\) | ms    |      | 0.31       |      |       |        |

\(a\)Rest-frame value. Error is dominated by uncertainty in \(n_e\).

\(b\)Assumes \(v = 1\)GHz, \(n_e = 4 \times 10^{-3} \text{ cm}^{-3}\), \(z_{\text{DLA}} = 1\), \(z_{\text{source}} = 2\).