Galactic contribution to the dispersion measure of extragalactic fast radio bursts

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ABSTRACT

We provide an empirical list of the Galactic dispersion measure (DM_{Gal}) contribution to the extragalactic fast radio bursts along 72 sightlines. It is independent of any model of the Galaxy, i.e., we do not assume the density of the disk or the halo, spatial extent of the halo, baryonic mass content, or any such external constraints to measure DM_{Gal}. We use 21-cm, UV, EUV and X-ray data to account for different phases, and find that DM_{Gal} is dominated by the hot phase probed by X-rays. The median DM_{Gal} = 64^{+20}_{−23} cm^{-3} pc, with a 68% (90%) confidence interval of 33–172 (23–660) cm^{-3} pc. The DM_{Gal} does not appear to follow any trend with the galactic longitude or latitude, and there is a large scatter around the values predicted by simple disk+halo models. Our measurements provide complementary (if not better) estimates of the Galactic DM compared to the previous studies. We provide a table and a code to retrieve DM_{Gal} for any FRB localized in the sky.

Keywords: X-ray astronomy–FRB–dispersion measure–Quasar absorption-line spectroscopy

1. INTRODUCTION

Fast radio bursts (FRBs) are bright (50 mJy–100 Jy) coherent pulses of emission at radio frequencies, with duration of order milliseconds or less (Lorimer et al. 2007; Petroff et al. 2019). The intervening plasma through which the pulses travel imposes a refractive index that retards the group velocity as a function of frequency. This leads to a time delay (∆t) between the highest (ν_h) and lowest (ν_l) radio frequencies of the pulse, quantified by the dispersion measure (DM): DM ∝ ∆t/(ν_l−ν_h). The DM of an FRB at redshift z is defined as DM = ∫ n_e dl, a line-of-sight integration of the free-electron number density of the intervening medium. Typically, the DM of FRBs are hundreds of cm^{-3} pc (Petroff et al. 2016), which is too large to be explained by the electrons in the interstellar medium (ISM) of the Milky Way (Cordes & Lazio 2002; Dolag et al. 2015; Yao et al. 2017). This indicates that FRBs are extragalactic.

The extragalactic origin of FRBs makes it a promising tool to probe the otherwise invisible ionized intergalactic medium. Over the past decade, many uses of the DM of FRBs have been proposed, such as to study the cosmic reionization history, large-scale structure of the universe, cosmic proper distance measurements, baryon fraction of the intergalactic medium (IGM), and precision cosmology (Zheng et al. 2014; Masui & Sigurdson 2015; Yu & Wang 2017; Li et al. 2019; Macquart et al. 2020, and references therein).

The observed DM toward FRBs includes the DM of the host galaxy (DM_{host}), the intergalactic medium (IGM; DM_{IGM}), the Local Group, and the Milky Way. For any cosmological calculation using the DM of FRBs, it is necessary to know and remove the Galactic contribution, DM_{Gal} from the total observed DM. By Galactic, we mean primarily the ISM in the disk and the circumgalactic medium (CGM) in the halo of the Milky Way. Because of the unknown spatial extent of the Galactic halo, the DM signatures of the Local Group and the Galaxy halo become observationally indistinguishable, broadly providing the z ≈ 0 value.

The surveys searching for FRBs usually set a cutoff on the DM such that the DM of a detected FRB is larger than the Galactic DM (Petroff et al. 2019). Also, the DM_{IGM}–z relation can be used to roughly estimate the redshift of an FRB (Zheng et al. 2014; Li et al. 2019), and to estimate DM_{IGM} the knowledge of DM_{Gal} is essential. Therefore, it is important to have a detailed understanding of the sky distribution of the Galactic DM to efficiently detect FRBs and to measure their distances, which again is instrumental for cosmological studies.

Yamasaki & Totani (2020) prescribed a disk and spherical halo density model from the X-ray emission measure of the Galactic halo along > 100 sightlines and predicted the Galactic DM contribution based on that
model. This model is better than previous models which ignored the halo component for simplicity (e.g., Cordes & Lazio 2002; Yao et al. 2017).

As emission measure (EM) is proportional to the density squared \( EM = \int n_e n_p dl \), it is not possible to retrieve the dispersion measure without constructing a density model. Often, such models depend on many parameters including the spatial extent of the Galactic halo, the baryon fraction in the halo and the virial mass of Milky Way. However, none of these quantities are well-constrained and the spatial extent varies wildly all over the sky (see Boylan-Kolchin et al. 2013; Gupta et al. 2012, 2017, for details). This leads to a huge systematic uncertainty which usually surpasses the statistical uncertainty of the emission measurements from which the density model is constructed.

On the other hand, the column density \( N_X = \int n_X dl \) from absorption analyses can be directly converted to the dispersion measure assuming some ionization condition. Prochaska & Zheng (2019) used the column densities of O\( ^{\text{VII}} \) K-\( \alpha \) lines from Fang et al. (2015) to calculate the DM contribution of the hot Galactic halo. The equivalent widths of the O\( ^{\text{VII}} \) K-\( \alpha \) lines indicate that many lines are saturated but not damped. The spectral resolution of the Reflection Grating Spectrometer (RGS) of \textit{XMM-Newton} is not good enough to resolve the O\( ^{\text{VII}} \) line and obtain the velocity width. Therefore, the Voigt profile fitting, as has been done in Fang et al. (2015), might not be an accurate way to obtain the column density of these lines. Instead, the equivalent widths of the O\( ^{\text{VII}} \) K-\( \alpha \) and O\( ^{\text{VII}} \) K-\( \beta \) lines can be combined to constrain the column density and the velocity width (e.g., Nicastro et al. 2002; Williams et al. 2005; Gupta et al. 2012; Nicastro et al. 2016a; Gupta et al. 2017); this is our approach for calculating the O\( ^{\text{VII}} \) column densities in this paper. We provide an empirical estimation of the DM contribution of the Galactic disk and halo from the X-ray absorption analyses. For completeness, we have considered other phases, although those are not the primary contributors. Instead of constructing a density model, we provide the DM along the observed sightlines. It is a more appropriate representation of the Galactic DM contribution than the previous estimates.

This paper is organized as follows. In section 2 we discuss the steps to calculate the Galactic dispersion measure. In section 3 we show how the Galactic dispersion measure contribution is distributed over the sky and compare it with previous models. Finally in section 4 we summarize the result and outline the future plans to improve upon this work.

2. ANALYSIS

We have accumulated the data from the literature in different wavelengths, and converted them to the dispersion measure without assuming any density model.

The Galactic dispersion measure (DM) contribution should be a combination of the disk and the halo in four different phases:

\[
DM_{\text{Gal}} = DM_{\text{cold}} + DM_{\text{cool}} + DM_{\text{warm}} + DM_{\text{hot}}
\]  

Here, “cold” refers to \( \approx 10^4 \text{K} \) gas which is predominantly neutral, “cool” is \( 10^4-5 \times 10^5 \text{K} \) mildly ionized gas, “warm” is for \( 10^5-5.5 \text{K} \) gas probed by primarily O\( ^{\text{VI}} \), and hot refers to \( \geq 10^6 \text{K} \) gas probed by H- and He-like ions, e.g., O\( ^{\text{VII}} \) and O\( ^{\text{VIII}} \) (Timlinson et al. 2017).

We obtain \( DM_{\text{cold}} \) from the 21-cm H\( ^{\text{I}} \) emission measurement at \( z = 0 \) (HI4PI Collaboration et al. 2016)\(^1\) using the following equation:

\[
DM_{\text{cold}} = 6.5 \text{cm}^{-3} \text{pc} \left( \frac{N_{\text{HI}}}{10^{21} \text{cm}^{-2}} \right) \left( \frac{x_e}{0.02} \right)
\]  

Here, \( x_e = \frac{2n_e}{n_H} \) is the electron fraction, which is typically 0.02 for a \( \approx 10^4 \text{K} \) gas (Draine 2011).

The cool gas is probed by singly/doubly ionized gas (e.g., Si\( ^{\text{II}} \) and Si\( ^{\text{III}} \) ions). By assuming that the element is in only two ionization states, we obtain \( DM_{\text{cool}} \) from the column densities of Si\( ^{\text{II}} \) and Si\( ^{\text{III}} \) ions (also C\( ^{\text{II}} \) and C\( ^{\text{IV}} \) ions) using the following equation:

\[
DM_{\text{cool}} = 5.3 \text{cm}^{-3} \text{pc} \left( \frac{A_{\text{Si,}0}}{2 \times 10^{13.3} \text{cm}^{-2}} \right) \left( \frac{Z}{0.1 Z_{\odot}} \right)^{-1}
\]

Here, we scale with respect to the median column density of Si\( ^{\text{II}} \) and Si\( ^{\text{III}} \) in the intermediate and high velocity absorbers in the Galactic halo (Richter et al. 2017), corrected by a factor of 2 to account for the low velocity absorbers (Zheng et al. 2015). \( A_{\text{Si,}0} \) is the solar abundance of silicon (Asplund et al. 2009). The typical metallicity is taken to be 0.1 \( Z_{\odot} \) (Wakker 2001). A similar calculation with C\( ^{\text{II}} \) and C\( ^{\text{IV}} \) from Richter et al. (2017) yields a DM value of 3.2 cm\(^{-3}\) pc.

The assumption of all Si\( ^{\text{II}} \) and Si\( ^{\text{III}} \) coming from the same medium might not generally be true. The cool phase is photo-ionized, and the uncertainties related to photo-ionization are large. The column densities of Si\( ^{\text{II}} \) and Si\( ^{\text{III}} \) and their ratios span over an order of magnitude over the whole sky (Richter et al. 2017), indicating the complex thermal and ionization structure. For Carbon in the cool phase, observed absorption lines are from C\( ^{\text{II}} \) and C\( ^{\text{IV}} \), but not C\( ^{\text{III}} \), but in the photoionized gas C\( ^{\text{III}} \) must exist together with C\( ^{\text{II}} \) and C\( ^{\text{IV}} \). This will make \( DM_{\text{cool}} \) based on Carbon, similar than from Si.

It should be noted that all of the H\( ^{\text{I}} \) measured in 21-cm might not come from a predominantly neutral medium. If H\( ^{\text{I}} \) comes from an ionized medium, \( DM_{\text{cold}} \), the DM in the cold phase, would be lower. One would

\(^1\) https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
generally expect denser mediums (i.e., with \((\text{N(H)} \geq 10^{20} \text{ cm}^{-2})\) to be more shielded and hence predominantly neutral, while smaller \(\text{N(H)}\) values can come from a partially ionized medium. Based on the typical \(\text{N(H)}\) values in the cool phase, we estimate an approximate DM. The average ionization fraction of \(\text{H} \), \(f_{\text{H}} = 0.3\) in the cool phase (Lehner & Howk 2011; Putman et al. 2012; Richter et al. 2017). The median \(\text{N(H)}\) in HI4PI Collaboration et al. (2016) is \(\text{N(H)} = 4.3 \times 10^{18} \text{ cm}^{-2}\). The DM for this median \(\text{N(H)}\) and average \(f_{\text{H}}\) would be 6.5 cm\(^{-3}\) pc, including the correction factor of 2 to account for the low velocity gas (Zheng et al. 2015).

This is comparable with \(\text{DM}_{\text{cool}}\) obtained from silicon and carbon lines using equation 3, as was also found by Prochaska & Zheng (2019). Therefore, between the cold and cool phases, the sightlines with high \(\text{N(H)}\) are likely to have a higher \(\text{DM}_{\text{cool}}\) and the smaller \(\text{N(H)}\) would contribute higher \(\text{DM}_{\text{cool}}\). As the DM calculated from metal lines and \(\text{H} \) are comparable, we consider the DM calculated from metal lines as the bulk estimate of \(\text{DM}_{\text{cool}}\). To avoid double counting, we do not include the cool phase in the final calculation. If along a given sightline \(\text{DM}_{\text{cool}} < \text{DM}_{\text{cool}}\) indicating that DM is dominated by the cool phase rather than the cold phase, \(\text{DM}_{\text{cool}}\) might be added to the final calculation of \(\text{DM}_{\text{Gal}}\).

We estimate the DM contribution of the warm phase using

\[
\text{DM}_{\text{warm}} = 4.4 \text{ cm}^{-3} \text{pc} \left( \frac{N_{\text{OVII}}}{2 \times 10^{14.3} \text{ cm}^{-2}} \right) \left( f_{\text{OVII}} \right) \left( \frac{A_{\odot}}{0.2} \right) \left( \frac{Z}{4.9 \times 10^{-4}} \right) \left( \frac{0.3 Z_{\odot}}{Z} \right)^{-1}
\]

Here, we scale with respect to the median column density of \(\text{OVII}\) in the intermediate and high velocity absorbers in the Galactic halo (Sembach et al. 2003), corrected by a factor of 2 to account for the low velocity absorbers (Zheng et al. 2015). \(A_{\odot}\) is the solar abundance of oxygen (Asplund et al. 2009). The typical metallicity is taken to be 0.3 \(Z_{\odot}\), the median metallicity of the warm CGM of L* galaxies in the COS-Halos sample (Prochaska et al. 2017). The uncertainties related to the photo-ionization modeling of \(\text{OVII}\) are large, so we adopt the maximum ionization fraction of \(f_{\text{OVII}} = 0.2\), where the detection of \(\text{OVII}\) is most likely.

The DM contribution of the hot phase is calculated by two methods. First, we calculate the DM from \(\text{OVII}\) and \(\text{OVIII}\), if available) line measurement by Gupta et al. (2012); Nicastro et al. (2016a); Gupta et al. (2017) using the following equation:

\[
\text{DM}_{\text{hot}} = 83.7 \text{ cm}^{-3} \text{pc} \left( \frac{N_{\text{OVII}}}{10^{16.3} \text{ cm}^{-2}} \right) \left( f_{\text{OVIII}} \right) \left( \frac{A_{\odot}}{0.2} \right) \left( \frac{Z}{4.9 \times 10^{-4}} \right) \left( \frac{0.3 Z_{\odot}}{Z} \right)^{-1}
\]

If both \(\text{OVII}\) and \(\text{OVIII}\) are detected or an upper limit exists along a sightline, the temperature (or its upper limit) of the gas is calculated from their column density ratio, \(\frac{N_{\text{OVIII}}}{N_{\text{OVII}}}\), assuming that the gas is in collisional ionization equilibrium (CIE). The ionization fraction of \(\text{OVII}\), \(f_{\text{OVII}}\) at that temperature is used to calculate \(\text{DM}_{\text{hot}}\). Along some sightlines, the measurement of the \(\text{OVIII}\) line is not reported. This is either because \(\text{OVIII}\) line was too weak to obtain a measurement of the column, or \(\text{OVIII}\) could not be studied due to instrumental features at that wavelength. In these cases, we assume \(f_{\text{OVII}} = 1^2\). As metallicity cannot be measured in X-ray absorption due to the lack of a hydrogen line, we adopt the same metallicity in the hot and warm phases, assuming that the warm phase forms by cooling from the hot phase.

The second method is based on the \(\text{N(H)}\) values of the hot phase estimated by Gatuzz & Churazov (2018). There, the oxygen lines have been fitted using hybrid ionization modeling\(^1\), for a constant temperature of \(10^6\text{K}\). We take \(\text{N(H)}\) in the hot phase for solar metallicity from Gatuzz & Churazov (2018)\(^4\), and convert it to \(\text{DM}_{\text{hot}}\) using

\[
\text{DM}_{\text{hot}} = 85.6 \text{ cm}^{-3} \text{pc} \left( \frac{N_{\text{H}}}{10^{20.3} \text{ cm}^{-2}} \right) \left( \frac{Z}{0.3 Z_{\odot}} \right)^{-1}
\]

The \(\text{N(H)}\) of the cold phase was part of their model, whose value is not necessarily the same as the 21-cm measurement by HI4PI Collaboration et al. (2016). Therefore, we calculate \(\text{DM}_{\text{cold}}\) of the Gatuzz & Churazov (2018) sightlines from their estimated \(\text{N(H)}\) of the cold phase. Thus the total \(\text{DM}_{\text{Gal}}\) from Gatuzz & Churazov (2018) is ionization model-based, while other estimations (Gupta et al. 2012; Nicastro et al. 2016a) are empirical.

The typical DM contribution of the hot phase exceeds that of any other phase by almost an order of magnitude. Therefore, inclusion of those phases does not significantly affect the total Galactic DM contribution. Nonetheless, we add the contribution of the cold phase, because:

1) unlike the cool and warm phases, the 21-cm data is available along all the sightlines where X-ray data are available,

2) the DM contribution from the cool and warm phases are complicated by the uncertainties related to photo-ionization. The calculation in the cold phase, however, is straightforward, and

\(\text{DM}_{\text{hot}}\) is a critical parameter in their model.

\(^1\) The maximum ionization fraction of \(\text{OVII}\) in CIE is \(\approx 0.9\). But the measurement uncertainty in the column density of \(\text{OVII}\) is much larger than this uncertainty in the ionization fraction. This validates the assumption of \(f_{\text{OVII}} = 1\).

\(^2\) The photo-ionization parameter is negligibly small in their model. Therefore, effectively, the model is collisional ionization.

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\(^4\) The photo-ionization parameter is negligibly small in their model. Therefore, effectively, the model is collisional ionization.
Figure 1. Dispersion measure (DM) contribution of the Galactic disk and halo as a function of galactic longitude (left) and latitude (right). The data points are derived from the 21-cm and X-ray absorption measurement of the cold (HI4PI Collaboration et al. 2016) and hot (Gupta et al. 2012; Nicastro et al. 2016a; Gupta et al. 2017; Gatuzz & Churazov 2018) Galactic halo. The filled circles denote the sightlines where both $O_{\text{vii}}$ and $O_{\text{viii}}$ lines were detected, the unfilled circles are where upper limits of $O_{\text{viii}}$ were reported, squares denote the sightlines where the value of $O_{\text{viii}}$ line was not reported and $f_{O_{\text{vii}}}$ is assumed to be 1 to calculate DM. Top: The gray regions denote the range of the pulsar dispersion measure towards LMC and SMC (Ridley et al. 2013, and references therein). The horizontal dashed line is the median of DM contribution of the cool and warm phases (Richter et al. 2017; Sembach et al. 2003). Bottom: The gray region is the predicted Galactic DM contribution modeled from the emission measure of hot Galactic halo (Yamasaki & Totani 2020).

3) the relative contribution of the cold and hot phase may vary wildly over the sky because of the known anisotropy of the hot phase in the Galactic halo (Henley et al. 2010; Gupta et al. 2012, 2017; Nakashima et al. 2018).

3. RESULTS AND DISCUSSION

We show the Galactic dispersion measure as a function of the galactic coordinates in Figure 1. We also plot the median DM contribution of the cool and warm phases to show that their values are negligible compared to the DM from the hot (and cold) phases (Figure 1, top). The pulsar dispersion measure toward LMC and SMC (Ridley et al. 2013) are comparable with the DM values we obtain, validating the assumption of the 0.3 $Z_{\odot}$ metallicity in the hot phase.

The DM profile from the density model of Yamasaki & Totani (2020) is shown for comparison (Figure 1, bottom). The range of DM values at a given galactic latitude (longitude) corresponds to the DM values spanning the whole range of galactic longitude (latitude). On av-
average, the model does a pretty good job of predicting the Galactic DM. However, the exact DM value along many sightlines deviate significantly from the predicted profile, both at small and large (l, b). This shows that not even all the disk dominated sightlines can be explained by the disk+halo model. As the measurement of FRB DM is sightline specific, the estimation of Galactic DM and the cosmological calculations following that can be drastically incorrect if we use an average value. Therefore, the empirical values we present here are more accurate than the previously modeled values.

Most of the sightlines have been observed with multiple instruments (Chandra and XMM-Newton) and/or multiple methods (direct measurement of absorption lines or ionization modeling). The DM estimates along some of the sightlines are not consistent with each other within error. This might partially be due to the assumption about the temperature (Figure 2). For simplicity, Gatuzz & Churazov (2018) assumed a constant temperature of $10^{6.3}$ K for all the sightlines. While this assumption is generally true, the temperature obtained from the ratio of N(O viii) and N(O vii) along every sightline is not necessarily the same. Because the ionization fraction of O vii changes sharply around $10^{6.3}$ K, the DM estimation is very sensitive to the temperature of the hot component. On the other hand, the ionization model might have a better continuum (and hence absorption line) estimation than the direct line measurements. The model simultaneously take into account of multiple phases, including the absorption lines of multiple elements in addition to O vii and O viii. Therefore, we do not have any particular reason to prefer one method over the other.

The DM$_{Gal}$ does not have any trend with either of the galactic coordinates (Figure 1). There is more than two orders of magnitude scatter in the values of the DM$_{Gal}$. This shows that the geometrically ordered structures like the spherical halo and the disk might not explain the observation well. As DM$_{Gal}$ is dominated by DM$_{hot}$, this pattern of DM reflects the characteristics of the hot Galactic halo. This is consistent with the X-ray emission and absorption analyses which report the hot Galactic halo to be inhomogeneous and anisotropic (Gupta et al. 2012; Henley & Shelton 2013; Nakashima et al. 2018).

In Figure 3 we show the sky distribution of Galactic DM contribution along with the DM of all FRBs discovered over past decade\(^5\). For the sightlines observed multiple times using different instruments and/or analyzed in different methods, we plot the average DM. We also calculate the maximum DM along each sightline (Table 5). The average DM should be the best estimate, while the maximum DM would provide a lower limit on the DM of the IGM.

\(^5\) The details of these FRBs are available at http://www.frbcat.org/

As can be seen in Figure 1, the distribution of DM$_{Gal}$ in the sky does not have any orderly pattern (Figure 3). Two sightlines far apart can have similar DM$_{Gal}$, while close-by sightlines show a scatter in DM$_{Gal}$. We do not find any systematic increase in DM$_{Gal}$ toward
Figure 3. The average Galactic dispersion measure (DM) contribution obtained from multiple methods (direct measurement of O\textsuperscript{vii} and O\textsuperscript{viii} lines vs. hybrid ionization modeling) and/or instruments (i.e., Chandra and XMM-Newton) in the Aitoff projection of galactic coordinates. The DM of the extragalactic FRBs observed in the past decade are plotted for comparison. The symbols are color-coded with the \( \log_{10} \) of DM; the filled circles are for the Galactic DM and the stars are for the FRB DM.

The direction of M\textsc{31} (\( l = 121.17^\circ, b = -21.57^\circ \)), indicating that the halo of M\textsc{31} might not have a significant contribution to the measured DM\textsubscript{Gal}. Thus, interpolation of DM\textsubscript{Gal} values might not be the correct approach due to its non-monotonic behavior as a function of the galactic coordinates. This shows how complex the distribution of density, spatial extent, temperature and ionization state of the Galactic disk and halo are, and how challenging the modeling is to explain the details of the multi-wavelength observation.

We perform a Kendall’s \( \tau \) test to verify any correlation between DM\textsubscript{Gal} and the galactic coordinates (Table 1). We do not include the lower limits and upper limits in this test. The value of \( \tau = +1/-1/0 \) implies a perfect positive/negative/null correlation, and the p-value is the probability of a null correlation. The all-sky distribution of DM\textsubscript{Gal} has a |\( \tau \) | < 0.1 and a \( \approx 50\% \) probability of any correlation with \( l \) or \( b \). The lack of correlation between DM\textsubscript{Gal} and \( b \) becomes more prominent when the extragalactic sightlines (\( |b| > 20^\circ \)) or off-center sightlines (\( 20^\circ < l < 340^\circ \)) are considered; the probability of a null correlation enhances to 96\% and 77\%, respectively. This shows why the disk model is not a good representation of the DM\textsubscript{Gal} distribution. The lack of strong anti-correlation between DM\textsubscript{Gal} and \( l \) indicates that the halo is not isotropic, and hence, a spherical model might not be appropriate either. The correlations (or the lack there of) are not exactly similar in the two hemispheres. DM\textsubscript{Gal} in the northern hemisphere shows a weak anti-correlation with \( b \), while the southern hemisphere shows a weak positive correlation. The probability of a null correlation with \( l \) is higher (71\%) in southern hemisphere than the northern hemisphere (37\%). These asymmetries are difficult to account for in the geometric density models. Once again, the empirical estimates are better.

Our correlation coefficients discussed in the previous paragraph are based on X-ray absorption studies along 72 sightlines. We compare these with the coefficients from Henley & Shelton (2013) based on X-ray emission
measures (EM) along 110 sightlines. The EM distribution did not show any dependence on \(|b|\) in either hemispheres, but there was significant \((p \ll 1)\) anti-correlation with \(l\) in southern hemisphere. This is different from our \(DM_{\text{Gal}}\) distribution. As the emission is dominated by denser regions, the disparity of correlations between EM and \(DM_{\text{Gal}}\) distribution indicates that the hot gas probed in emission and absorption might not be the same. This also adds to the reasons for using absorption analyses for DM measurements.

Next, we calculate the mean and the median of the \(DM_{\text{Gal}}\) distribution. Once again, We do not include the lower limits and upper limits. The average \(DM_{\text{Gal}}\) ranges from 12 to 1749 \(\text{cm}^{-3} \text{pc}\). This is larger than the ranges predicted by Prochaska \& Zheng (2019) based on the absorption analysis (50–80 \(\text{cm}^{-3} \text{pc}\)) and by Yamasaki \& Totani (2020) based on emission analysis (30–245 \(\text{cm}^{-3} \text{pc}\)). There are only 8 out of 72 sightlines with the average \(DM_{\text{Gal}} > 245 \text{ cm}^{-3} \text{pc}\), and 9 sightlines with the average \(DM_{\text{Gal}} < 30 \text{ cm}^{-3} \text{pc}\). That means the \(DM_{\text{Gal}}\) of most (76%) of the sightlines are consistent with the estimate of Yamasaki \& Totani (2020). The histogram of \(DM_{\text{Gal}}\) is asymmetric toward the higher values (Figure 4). This makes the mean (161 \(\text{cm}^{-3} \text{pc}\)) significantly higher than the median (64 \(\text{cm}^{-3} \text{pc}\)).

Please note that the \(DM_{\text{Gal}}\) values are not as robust as the \(N(\text{O vii})\) values. \(DM_{\text{Gal}}\) depends on both \(N(\text{O vii})\) and \(f_{\text{O vii}}\) (see equation 5). The uncertainty in the value of \(f_{\text{O vii}}\) depends on the robustness of temperature as well as the value of \(f_{\text{O vii}}\) at the temperature of the hot gas. The temperature depends on \(N(\text{O viii})\) and \(N(\text{O vii})\), the error in both oxygen lines are propagated in the uncertainty of the temperature, making it less constrained than the individual lines. If \(f_{\text{O vii}}\) changes rapidly within the range of the temperature of the hot gas, the uncertainty in \(DM_{\text{Gal}}\) will be driven by the uncertainty in \(f_{\text{O vii}}\), irrespective of how robust the \(\text{O viii}\) (and \(\text{O vii}\)) measurement is. Secondly, the estimated \(DM_{\text{Gal}}\) from multiple studies can be different due to the difference in method and/or instrument. This adds another uncertainty in \(DM_{\text{Gal}}\) when the values are averaged.

Keeping the above discussion in mind, we consider the distributions of \(DM_{\text{Gal}} - \sigma_{l}\) and \(DM_{\text{Gal}} + \sigma_{u}\). Here \(\sigma_{l}\) and \(\sigma_{u}\) are the statistical uncertainty of the average \(DM_{\text{Gal}}\) in the lower and the upper end, respectively. The median of these two distributions provide an uncertainty in the median of the \(DM_{\text{Gal}}\) distribution. We find that median \(DM_{\text{Gal}} = 64_{-23}^{+20} \text{ cm}^{-3} \text{pc}\) (Figure 4). Additionally, we calculate the uncertainty in the mean by propagating the uncertainty of individual sightlines assuming Poissonian statistics, and obtain mean \(DM_{\text{Gal}} = 161_{-32}^{+243} \text{ cm}^{-3} \text{pc}\). The 68% (90%) confidence interval of the \(DM_{\text{Gal}}\) distribution is 33–172 (23–660) \(\text{cm}^{-3} \text{pc}\). Our typical \(DM_{\text{Gal}}\) is larger than the mean based on density models and cosmological hydrodynamic simulations.

Figure 4. The histogram of Galactic dispersion measure in log\(_{10}\) scale. The distribution is asymmetric, with a tail toward higher values. This is reflected by the stark difference between the median and the mean of the distribution. The hatched region corresponds to the uncertainty in the median. The dark (light) shaded region corresponds to 68% (90%) confidence interval. Overall, our estimate of Galactic DM is larger than the previous estimates. The mean of those estimates are shown for comparison.

(43 and 30 \(\text{cm}^{-3} \text{pc}\), respectively; Dolag et al. 2015; Yamasaki \& Totani 2020).

3.1. Utility

For an FRB localized in the sky, one needs to find the closest sightlines (i.e., the sightlines at smallest angular separation from the FRB) and obtain the mean of the Galactic DM along those sightlines. This would be the Galactic contribution to the total DM toward that FRB. The choice of the statistic (e.g., mean, median or interpolation) to combine multiple sightlines and the upper limit of angular separation to consider sightlines within may vary with the scientific purpose. Using the \(DM_{\text{Gal}}\) of a single sightline would be the simplest option, although that might not be the most accurate estimate.

We attach a machine readable file with the paper. It has the galactic longitude and latitude, average \(DM_{\text{Gal}}\) and associated statistical and systematic uncertainty, and the maximum \(DM_{\text{Gal}}\) along all sightlines considered here. The systematic uncertainty along a sightline reflects the scatter between the individual estimates along that sightline. Thus, for the sightlines measured once, there is no systematic uncertainty. Statistical uncertainty along a sightline is obtained by propagating the uncertainty in individual measurement along that sightline in quadrature.

We build a code to extract the \(DM_{\text{Gal}}\) toward an FRB. We attach a copy of the code with the paper. It takes the
galactic coordinate of the FRB of consideration as system arguments in the units of degree, reads the galactic coordinates of the 72 sightlines from the file mentioned in the previous paragraph, calculates the angular distance between the FRB and all the sightlines and returns the best estimate of Galactic DM and associated error using the following 3 methods.

I) The DM_{Gal} and its statistical uncertainty along the sightline at smallest angular separation from the FRB.

II) The mean and the median of the sightlines within a threshold of angular separation from the FRB.

III) The mean and the median of the sightlines separated from the closest sightline within a tolerance limit. The threshold and the tolerance of angular separation in method II and III are taken as system arguments in the units of degree. We recommend the user to try different values of threshold and tolerance instead of fixed pre-conceived values, and wisely choose the statistic and the method depending on the scientific interest. This code can easily be extended to use the DM values from previous studies (e.g., Cordes & Lazio 2002; Yao et al. 2017; Prochaska & Zheng 2019; Yamasaki & Totani 2020) if a nearby sightline within the user's choice of threshold is not found. In this case, our code prompts a message asking to use the median of our DM_{Gal} distribution as an alternative to the earlier estimates. It should be clarified that the DM from cool and warm phases are not included in this (see §2 for details). If needed, one can add the median DM from these phases to the output of the code, although the resulting correction will be minimal.

3.2. Assumptions and caveats
In our calculation of DM_{Gal} we have assumed that the hot phase has a single temperature component. This is due to the limitation of observation rather than our method. In fact, any existing method to calculate DM lacks this information. However, there are certain sightlines where a hotter \( \approx 10^7 \) K component has been observed in absorption and/or emission (Henley & Shelton 2013; Nakashima et al. 2018; Das et al. 2019b,a, Gupta et al. 2020, in prep.). The electrons in this hot component would contribute significantly to the Galactic dispersion measure. The N(H) of the \( \approx 10^7 \) K component along 1ES 1553+113 \((l = 21.91^\circ, b = 43.96^\circ)\) was found to be an order of magnitude higher than the N(H) of the \( \approx 10^6 \) K component (Das et al. 2019b). Therefore, the DM_{hot} along this sightline would be higher than the current estimate by the same order. Using equation 6 for the N(H) estimates by Das et al. (2019b), we find that DM_{hot} \( \approx 128 \) cm\(^{-3}\) pc, while it is \( \approx 12 \) cm\(^{-3}\) pc from the N(H) estimate of Gatuzz & Churazov (2018). In fact, if multiple temperature components are present along a sightline, using the ratio of N(O viii) and N(O vii) to estimate \( f_{O \text{vii}} \) will be faulty as well, because it assumes that all of the O vii and O viii are coming from the same temperature component. Because the ubiquity of the hotter component is not known yet, we do not include the contribution of the hotter component in our final list. The list should be updated after re-analyzing the sightlines searching for the hotter component. This may significantly change the DM_{Gal} distribution in Figure 3.

In our analysis we assumed that all of the O vii comes from the hot phase. But the warm phase probed by O vi should also have some O vii. This warm phase O vii should be subtracted from the total measured O vii to determine the hot phase O vii. This would require simultaneous measurement of O vi, O vii and O viii along all sightlines, and a self-consistent hybrid ionization modeling of these three ionization states. We do not have such data for all the X-ray sightlines. If all of the oxygen in the warm phase is in O vi and O vii, from the median column density and ionization fraction of O vi we can obtain the median N(O vii) in the warm phase. This is \( \approx 10^{15.5} \) cm\(^{-2}\), an order-of magnitude smaller than the median N(O vii) in the hot phase (see eq. 4 and 5). This shows our calculation will not change significantly after accounting of the O vii in multiple phases.

The spectral resolution of the gratings in Chandra and XMM-Newton cannot distinguish between the Galactic halo and the Local Group medium. Therefore, the measured column densities of O vii and O viii and the dispersion measure calculated from that might contain a Local Group component. The Galactic halo is collisionally ionized, but the Local Group medium will have a smaller density and thus a non-negligible photo-ionized phase. In that case, the ionization fraction of O vii in equation 5 and the calculation following that will have to be corrected for photo-ionization. This is beyond the scope of this paper. Using higher resolution data, it will be possible to obtain the kinematic and spatial information of the absorption lines, which will be essential for a multi-component hybrid ionization modeling.

The absorption sightlines do not have an all sky-coverage unlike the models (Cordes & Lazio 2002; Yao et al. 2017; Yamasaki & Totani 2020). Therefore, in the absence of a sightline with known DM_{Gal} close to the sightline of an FRB, it has to be approximated with 1) the previous estimates based on the density distribution of the Galactic disk and halo, and/or 2) the median with a confidence interval of our DM_{Gal} estimation.

4. CONCLUSION
Based on 21-cm, UV and X-ray absorption analyses at \( z = 0 \) along 72 sightlines, we provide an empirical list of the Galactic dispersion measure contribution to the extragalactic fast radio bursts. It is independent of any density model and the spatial extent of the Galactic halo. Our findings are:

1) DM_{Gal} is dominated by the hot phase probed by X-ray absorption.

2) There is no definite trend of DM_{Gal} with respect to...
the galactic coordinates.

3) The previous models on average are consistent with our measurements, but there are a few sightlines where our measurements are significantly different.

4) The median \( \text{DM}_{\text{Gal}} = 64^{+20}_{-23} \) cm\(^{-3}\) pc, with a 68% (90%) confidence interval of 33–172 (23–660) cm\(^{-3}\) pc.

We provide a table and a code to retrieve \( \text{DM}_{\text{Gal}} \) for any FRB localized in the sky. This should provide a complementary (if not better) estimate of the Galactic DM compared to the previous studies.

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**Software:** NumPy v1.11.0 (Dubois et al. 1996), Matplotlib v1.5.3 (Hunter 2007), Scipy v.17.0 (Oliphant 2007)

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Table 2. DM$_{\text{hot}}$ based on the O$_{\text{vii}}$ and O$_{\text{viii}}$ measurements of Gupta et al. (2012, 2017) and DM$_{\text{cold}}$ based on the 21-cm measurements of HI4PI Collaboration et al. (2016). The last two columns denote the uncertainty in DM$_{\text{hot}}$.

| Target     | l     | b     | DM$_{\text{cold}}$ | DM$_{\text{hot}}$ | e$_{\text{low}}$ | e$_{\text{up}}$ |
|------------|-------|-------|--------------------|-------------------|------------------|----------------|
|            | [deg] | [deg] | [cm$^{-3}$pc]      | [cm$^{-3}$pc]     | [cm$^{-3}$pc]    | [cm$^{-3}$pc]  |
| Both O$_{\text{vii}}$ and O$_{\text{viii}}$ available: |
| 3C382      | 61.30 | 17.44 | 4.01               | 98.01             | 52.02            | 52.07          |
| ARK564     | 92.13 | -25.33| 3.23               | 43.86             | 34.40            | 20.12          |
| H2106-099  | 40.26 | -34.93| 4.17               | 130.50            | 112.98           | 60.80          |
| Mrk290     | 91.48 | 47.95 | 1.41               | 53.25             | 25.58            | 23.94          |
| Mrk421     | 179.83| 65.03 | 0.87               | 47.77             | 12.77            | 12.70          |
| Mrk 509$^a$| 35.97 | -29.86| 2.56               | 156.61            | 48.98            | 48.25          |
| NGC3783    | 287.45| 22.94 | 6.49               | 62.10             | 19.52            | 18.93          |
| PKS2155-304| 17.73 | -52.24| 0.83               | 47.46             | 14.13            | 12.75          |

Only O$_{\text{vii}}$ available. $f_{\text{O_{vii}}} = 1$:

| Target     | l     | b     | DM$_{\text{cold}}$ | DM$_{\text{hot}}$ | e$_{\text{low}}$ | e$_{\text{up}}$ |
|------------|-------|-------|--------------------|-------------------|------------------|----------------|
|            | [deg] | [deg] | [cm$^{-3}$pc]      | [cm$^{-3}$pc]     | [cm$^{-3}$pc]    | [cm$^{-3}$pc]  |
| 1ES1927+654| 96.98 | 20.96 | 4.16               | 41.95             | 16.75            | 16.75          |
| 3C273      | 289.95| 64.36 | 1.09               | 22.53             | 6.07             | 6.07           |
| BL0502+675 | 143.79| 15.89 | 5.99               | 32.56             | 12.69            | 12.69          |
| H1426+428  | 77.49 | 64.90 | 0.62               | 22.53             | 8.14             | 8.14           |
| H1821+643  | 94.00 | 27.42 | 2.27               | 16.32             | 6.98             | 6.98           |
| H2356-309  | 12.84 | -78.04| 0.77               | 12.96             | 6.42             | 6.42           |
| MRC2251-178| 46.20 | -61.33| 1.71               | 25.87             | 13.32            | 13.32          |
| Mrk279     | 115.04| 46.86 | 0.84               | 22.02             | 4.98             | 4.98           |
| NGC3516    | 133.24| 42.40 | 1.99               | 34.10             | 10.73            | 10.73          |
| NGC4505    | 148.88| 70.09 | 0.77               | 31.10             | 8.94             | 8.94           |
| NGC4593    | 297.48| 57.40 | 1.08               | 23.05             | 11.87            | 11.87          |
| NGC5548    | 31.96 | 70.50 | 1.01               | 8.37              | 6.53             | 6.53           |
| NGC7469    | 83.10 | -61.33| 2.91               | 10.54             | 6.87             | 6.87           |

$^a$From hybrid ionization modeling by Gupta et al. (2017), DM$_{\text{hot}} = 89.16^{+47.78}_{-29.94}$ cm$^{-3}$pc

Table 3. DM$_{\text{hot}}$ based on the O$_{\text{vii}}$ and O$_{\text{viii}}$ measurements of Nicastro et al. (2016a) and DM$_{\text{cold}}$ based on the 21-cm measurements of HI4PI Collaboration et al. (2016). The last two columns denote the uncertainty in DM$_{\text{hot}}$.

| Target     | l     | b     | DM$_{\text{cold}}$ | DM$_{\text{hot}}$ | e$_{\text{low}}$ | e$_{\text{up}}$ |
|------------|-------|-------|--------------------|-------------------|------------------|----------------|
|            | [deg] | [deg] | [cm$^{-3}$pc]      | [cm$^{-3}$pc]     | [cm$^{-3}$pc]    | [cm$^{-3}$pc]  |
| Both O$_{\text{vii}}$ and O$_{\text{viii}}$ available: |
| SAXJ1808.4-3658 | 355.39 | -8.15 | 7.78               | 63.79             | 12.48            | 13.23          |
| XTEJ1650-500   | 336.72 | -3.43 | 39.56              | 179.79            | 33.71            | 481.70         |
| SwiftJ1753.5-0127 | 24.90 | 12.19 | 14.92              | 51.56             | 8.06             | 11.55          |
| CYGX-2        | 87.33 | -11.32| 12.97              | 57.16             | 7.00             | 8.46           |
| 4U1543-62     | 321.76| -6.34 | 14.27              | 87.76             | 10.75            | 363.43         |
| AqlX-1        | 35.72 | -4.10 | 25.29              | 79.21             | 9.70             | 21.72          |
| SWIFTJ1910.2-0546 | 29.91 | -6.82 | 22.70              | 53.42             | 7.57             | 12.31          |
| 4U1636-536    | 332.91| -4.82 | 23.99              | 103.86            | 20.85            | 33.69          |
| Source          | $V_e$   | $V_b$   | $V_{*}$ | $V_{82}$ | $V_{23}$ | $V_{32}$ |
|-----------------|---------|---------|---------|----------|----------|----------|
| 4U1735-44       | 346.05  | -6.99   | 18.81   | 110.52   | 13.53    | 25.01    |
| V*V821Ara      | 338.94  | -4.33   | 27.24   | 254.93   | 31.22    | 41.37    |
| GS1826-238      | 9.27    | -6.09   | 21.40   | 125.60   | 30.30    | 182.10   |
| HETEJ1900.1-2455 | 11.30  | -12.87  | 8.43    | 491.95   | 178.64   | 1294.30  |
| 3C273           | 289.95  | 64.36   | 1.30    | 141.49   | 25.73    | 35.69    |
| PG1553+113      | 21.91   | 43.96   | 2.59    | 106.77   | 13.47    | 14.47    |
| H1426+428       | 77.49   | 64.90   | 0.71    | 52.31    | 6.41     | 36.03    |
| PKS2005-489     | 350.37  | -32.60  | 2.59    | 345.43   | 42.30    | 614.90   |
| 3C390.3         | 111.44  | 27.07   | 2.59    | 209.90   | 29.50    | 5151.59  |
| HE1029-1401     | 259.33  | 36.52   | 3.89    | 491.95   | 178.64   | 1294.30  |
| Mrk501          | 63.60   | 38.86   | 3.57    | 75.94    | 9.30     | 83.83    |
| Mrk841          | 11.21   | 54.63   | 1.30    | 1243.36  | 1124.94  | 7710.06  |

Only $O_{\text{vii}}$ available. $f_{O_{\text{vii}}} = 1:\begin{align*}
PSRB0833-45 & : 263.55 \quad -2.79 \quad 1.95 \quad 31.76 \quad 16.35 \quad 39.89 \\
4U1728-16 & : 8.51 \quad 9.04 \quad 13.62 \quad 95.29 \quad 46.49 \quad 85.50 \\
X-Persei & : 163.08 \quad -17.14 \quad 12.97 \quad 148.23 \quad 136.21 \quad 21.01 \\
Mrk421 & : 179.83 \quad 65.03 \quad 1.23 \quad 31.76 \quad 4.70 \quad 4.70 \\
PKS2155-304 & : 17.73 \quad -52.25 \quad 0.97 \quad 132.35 \quad 45.35 \quad 45.35 \\
PKS-0558-504 & : 257.96 \quad -28.57 \quad 2.59 \quad 219.70 \quad 31.24 \quad 28.91 \\
MR2251-178 & : 46.20 \quad -61.33 \quad 1.56 \quad 211.76 \quad 13.49 \quad 31.87 \\
Mrk335 & : 108.76 \quad -41.42 \quad 2.59 \quad 79.41 \quad 43.45 \quad 101.05 \\
ESO141-G055 & : 338.18 \quad -26.71 \quad 3.24 \quad 39.70 \quad 19.16 \quad 32.13 \\
NGC7469 & : 83.10 \quad -45.47 \quad 3.37 \quad 97.94 \quad 67.25 \quad 16.00 \\
H/E1821+643 & : 94.00 \quad 27.42 \quad 2.20 \quad 952.91 \quad 828.82 \quad 13261.85 \\
NGC4593 & : 297.48 \quad 57.40 \quad 1.49 \quad 211.76 \quad 187.09 \quad 1059.11 \\
RE1034+396 & : 180.28 \quad 59.06 \quad 0.65 \quad 21.18 \quad 16.09 \quad 42.43 \\
UGC3973 & : 168.60 \quad 28.38 \quad 3.24 \quad 1455.84 \quad 1335.44 \quad 7942.92 \\
ESO198-G24 & : 271.64 \quad 67.95 \quad 1.75 \quad 3414.60 \quad 3361.29 \quad 11511.60 \\
1H0707-495 & : 260.17 \quad -17.67 \quad 2.59 \quad 211.76 \quad 187.09 \quad 900.34 \\
Akn564 & : 92.14 \quad -25.34 \quad 4.73 \quad 42.35 \quad 19.24 \quad 19.24 \\

$O_{\text{vii}}$ and 3σ upper limit of $O_{\text{viii}}$ available:

| Source          | $V_e$   | $V_b$   | $V_{*}$ | $V_{82}$ | $V_{23}$ | $V_{32}$ |
|-----------------|---------|---------|---------|----------|----------|----------|
| MAXIJ0556-332   | 238.94  | -25.18  | 2.59    | <87.06   | <35.56   |
| CYGNUSX-1       | 71.33   | 3.07    | 34.37   | <50.35   | <561.25  |
| 4U2129+12       | 65.01   | -27.31  | 5.19    | <5947.04 |
| PG1244+026      | 300.04  | 65.21   | 1.30    | <561.25  |
| Mrk279          | 115.04  | 46.86   | 0.97    | <318.92  |
| PG1211+143      | 267.55  | 74.32   | 1.95    | <7552.36 |
| H2356-309       | 12.84   | -78.04  | 0.98    | <147347.45 |
| 1ES1028+511     | 161.44  | 54.44   | 3.05    | <1652.78 |
| 3C120           | 190.37  | -27.40  | 6.49    | <113.02  |
| 1H0419-577      | 266.99  | -42.00  | 0.65    | <147347.45 |
| IRAS13224-3809  | 310.19  | 23.98   | 3.24    | <12352.57 |
| Mrk205          | 125.45  | 41.67   | 1.95    | <39861.25 |
| PG1116+215      | 223.36  | 68.21   | 0.65    | <154033.24 |
| Mrk704          | 213.82  | 39.72   | 1.95    | <3042.62 |

$f_{O_{\text{vii}}} = 1$, neglecting the upper limit of $O_{\text{viii}}$:
Table 4. \( DM_{\text{cold}} \) and \( DM_{\text{hot}} \) based on the ionization modeling of Gatuzz & Churazov (2018)

| Target          | l    | b    | \( DM_{\text{cold}} \) | err | \( DM_{\text{hot}} \) | err |
|-----------------|------|------|------------------------|-----|------------------------|-----|
| 4U 125469       | 303.48 | -6.42 | 20.75                  | 0.06 | 39.96                  | 6.32 |
| 4U 154362       | 321.76 | -6.34 | 15.37                  | 0.45 | 21.13                  | 11.97|
| 4U 163653       | 332.91 | -4.82 | 24.97                  | 0.65 | 32.45                  | 13.19|
| 4U 173544       | 346.05 | -6.99 | 23.67                  | 0.71 | 35.45                  | 13.70|
| 4U 182030       | 2.79  | -7.91 | 6.49                   | 0.39 | 24.28                  | 5.31 |
| 4U 191505       | 31.36 | -8.46 | 24.19                  | 1.36 | 31.25                  | 26.81|
| Aql X1          | 35.72 | -4.14 | 25.23                  | 0.26 | 19.96                  | 6.74 |
| Cygnus X2       | 87.33 | -11.32| 12.97                  | 0.13 | 12.02                  | 4.43 |
| GRO J165540     | 344.98 | 2.46  | 41.57                  | 0.32 | 28.60                  | 7.55 |
| GS 1826238      | 9.27  | -6.09 | 20.49                  | 0.26 | 48.05                  | 18.17|
| GX 3394         | 338.94 | -4.33 | 30.54                  | 0.39 | 43.66                  | 6.28 |
| GX 349+2        | 349.10 | 2.75  | 36.45                  | 1.04 | 29.26                  | 6.41 |
| GX 9+9/4U 172816| 8.51  | 9.04  | 21.01                  | 0.39 | 13.31                  | 5.14 |
| HETEJ1900.12455 | 11.30 | -12.87| 6.36                   | 0.13 | 7.55                   | 6.20 |
| SAX J1808.43658 | 355.39 | -8.15 | 6.42                   | 0.52 | 16.96                  | 3.67 |
| Ser X1          | 36.12 | 4.84  | 28.47                  | 0.45 | 20.97                  | 6.66 |
| Swift J1753.50127| 24.90 | 12.19 | 6.87                   | 0.06 | 12.57                  | 2.36 |
| XTE J1817330    | 359.82 | -8.00 | 13.75                  | 0.19 | 21.71                  | 3.79 |
| 1ES 1028+511    | 161.44 | 54.44 | 1.49                   | 0.51 | 18.42                  | 22.96|
| 1ES 1553+113    | 21.91 | 43.96 | 2.54                   | 0.26 | 11.67                  | 9.99 |
| 1ES 1927+654    | 96.98 | 20.96 | 5.96                   | 1.02 | 42.41                  | 53.18|
| 1H 0414+009     | 191.81 | -33.16| 6.15                   | 0.77 | 19.97                  | 32.81|
| 1H 0707495      | 260.17 | -17.67| 3.74                   | 0.25 | 21.01                  | 11.41|
| 1H 1426+428     | 77.49 | 64.90 | 1.14                   | 0.67 | 22.57                  | 19.97|
| 3C 120          | 190.37 | -27.40| 8.37                   | 0.30 | 26.33                  | 19.46|
Table 5. Average and maximum Galactic dispersion measure, combining multiple methods and instruments.

| Target                      | l   | b   | DM_{avg} | e_{low} | e_{up} | DM_{max} | e_{sys} |
|-----------------------------|-----|-----|----------|---------|--------|----------|---------|
|                             | [deg]| [deg]| [cm^{-3}pc] | [cm^{-3}pc] | [cm^{-3}pc] | [cm^{-3}pc] | [cm^{-3}pc] |
| one dataset                 |     |     |          |         |        |          |         |
| 4U 125469                   | 303.48 | -6.42 | 60.71 | 6.32 | 6.32 | 67.04 |        |
| 4U2129+12                   | 65.01 | -27.31 | 21.07 | 13.63 | 31.93 | 53.00 |        |
| 4U 182030                   | 2.79  | -7.91 | 30.77 | 5.33 | 5.33 | 36.09 |        |
| 4U 191505                   | 31.36 | -8.46 | 55.43 | 26.84 | 26.84 | 82.28 |        |
| CYGNUSX-1                   | 71.33 | 3.07  | 74.08 | 29.53 | 5.57 | 79.65 |        |
| GRO J165540                 | 344.98 | 2.46  | 70.17 | 7.55  | 7.55  | 77.72 |        |
| GX 349+2                    | 349.10 | 2.75  | 65.71 | 6.49  | 6.49  | 72.20 |        |
| X-Persei                    | 163.08 | -17.14 | 161.20 | 136.22 | 21.05 | 182.25 |        |

The table provides the average and maximum Galactic dispersion measure for various targets, combining multiple methods and instruments.
| Target                | l       | b       | DM$_{avg}$ | e$_{low}$ | e$_{up}$ | DM$_{max}$ | e$_{sys}$ |
|-----------------------|---------|---------|------------|-----------|----------|------------|-----------|
| MAXIJ0556-332         | 238.94  | -25.18  | 58.18      | 27.36     | 42.91    | 101.10     | —         |
| PSRB0833-45           | 263.55  | -2.79   | 33.71      | 16.36     | 39.90    | 73.61      | —         |
| Ser X1                | 36.12   | 4.84    | 49.44      | 6.68      | 6.68     | 56.12      | —         |
| SWIFTJ1910.2-0546     | 29.91   | -6.82   | 76.11      | 7.60      | 12.32    | 88.44      | —         |
| XTE J1817330          | 359.82  | -8.00   | 35.46      | 3.80      | 3.80     | 39.26      | —         |
| XTEJ1650-500          | 336.72  | -3.43   | 219.35     | 33.72     | 481.70   | 701.06     | —         |
| 3C 279                | 305.10  | 57.06   | 57.13      | 55.28     | 55.28    | 112.41     | —         |
| 3C 59                 | 142.04  | -30.54  | 40.97      | 27.11     | 27.11    | 68.07      | —         |
| Fairall 9             | 295.07  | -57.83  | 27.50      | 19.33     | 19.33    | 46.83      | —         |
| Mrk 1044              | 179.69  | -60.48  | 70.56      | 59.67     | 59.67    | 130.22     | —         |
| HE1029-1401           | 259.33  | 36.52   | 495.84     | 178.64    | 1294.30  | 1790.15    | —         |
| Mrk335                | 108.76  | -41.42  | 82.00      | 43.45     | 101.05   | 183.06     | —         |
| REI0344+396           | 180.28  | 59.06   | 21.82      | 16.09     | 42.43    | 64.26      | —         |
| UGC3973               | 168.60  | 28.38   | 1459.08    | 1335.44   | 7942.92  | 9402.00    | —         |
| PG1244+026            | 300.04  | 65.21   | 242.17     | 177.17    | 366.47   | 608.64     | —         |
| 1H0419-577            | 266.99  | -42.00  | 29.77      | 21.47     | 137.69   | 167.45     | —         |
| IRAS13224-3809        | 310.19  | 23.98   | 876.74     | 775.04    | 13023.55 | 13900.29   | —         |
| Mkn205                | 125.45  | 41.67   | 129.00     | 107.02    | 62.84    | 191.84     | —         |
| Mrk704                | 213.82  | 39.72   | 682.22     | 638.09    | 83.34    | 765.56     | —         |
| H2106-099             | 40.26   | -34.93  | 134.67     | 112.98    | 60.80    | 195.47     | —         |
| NGC4051               | 148.88  | 70.09   | 31.87      | 8.94      | 8.94     | 40.81      | —         |
| NGC3516               | 133.24  | 42.40   | 36.09      | 10.73     | 10.73    | 46.82      | —         |
| combined              |         |         |            |           |          |            |           |
| 4U 154362             | 321.76  | -6.34   | 69.26      | 6.59      | 148.45   | 465.46     | 32.77     |
| 4U 163653             | 332.91  | -4.82   | 92.63      | 10.08     | 14.78    | 161.55     | 35.22     |
| 4U 173544             | 346.05  | -6.99   | 94.22      | 7.87      | 11.65    | 154.34     | 35.10     |
| Aql X1                | 35.72   | -4.14   | 74.85      | 4.83      | 9.29     | 126.24     | 29.66     |
| Cygnus X2             | 87.33   | -11.32  | 47.56      | 3.39      | 3.91     | 78.62      | 22.57     |
| GS 1826238            | 9.27    | -6.09   | 107.78     | 14.42     | 74.71    | 329.10     | 39.23     |
| GX 3394               | 338.94  | -4.33   | 178.19     | 13.00     | 17.09    | 323.55     | 103.98    |
| GX 9+9/4U 172816      | 8.51    | 9.04    | 71.61      | 19.10     | 34.97    | 194.42     | 37.30     |
| HETEJ1900.12455       | 11.30   | -12.87  | 38.80      | 3.78      | 40.78    | 163.39     | 24.89     |
| SAX J1808.4358        | 355.39  | -8.15   | 47.48      | 5.32      | 5.61     | 84.82      | 24.09     |
| Swift J1753.50127     | 24.90   | 12.19   | 42.96      | 3.44      | 4.82     | 78.04      | 23.52     |
| 1ES 1028+511          | 161.44  | 54.44   | 90.89      | 55.41     | 583.67   | 1591.36    | 70.98     |
| 1ES 1553+113          | 21.91   | 43.96   | 61.79      | 6.85      | 7.18     | 123.83     | 47.57     |
| 1ES 1927+654          | 96.98   | 20.96   | 47.24      | 22.76     | 22.76    | 101.56     | 1.13      |
| 1H 0707495            | 260.17  | -17.67  | 119.55     | 76.52     | 367.59   | 1114.70    | 94.80     |
| 1H 1426+428           | 77.49   | 64.90   | 33.29      | 7.50      | 14.00    | 89.05      | 13.95     |
| 3C 120                | 190.37  | -27.40  | 28.53      | 10.28     | 21.03    | 70.05      | 6.16      |
| 3C 273                | 289.95  | 64.36   | 74.61      | 9.83      | 12.83    | 178.47     | 50.14     |
| 3C 382                | 61.31   | 17.45   | 94.63      | 31.96     | 31.97    | 154.09     | 7.39      |
Table 5 continued from previous page

| Target                  | l   | b   | DM$_{avg}$ | $e_{low}$ | $e_{up}$ | DM$_{max}$ | $e_{sys}$ |
|-------------------------|-----|-----|------------|-----------|----------|------------|-----------|
| 3C 390.3                | 111.44 | 27.07 | 148.73 | 19.35 | 2103.18 | 5395.08 | 94.77 |
| Ark 564                 | 92.14  | -25.34 | 37.18  | 13.35 | 9.57   | 67.21   | 14.01    |
| B0502+675               | 143.79 | 15.89 | 49.04  | 16.21 | 16.21  | 97.14   | 10.48    |
| ESO 141G055             | 338.18 | -26.71 | 51.98  | 12.78 | 16.56  | 85.79   | 9.04     |
| ESO 198G24              | 271.64 | -57.95 | 1748.83 | 1372.43 | 14552.68 | 14568.14 | 1667.71 |
| H2356309                | 12.84  | -78.04 | 36.82  | 17.86 | 46.29  | 215.70  | 29.01    |
| Mrk 279                 | 115.04 | 46.86 | 25.95  | 9.58  | 41.81  | 157.21  | 4.81     |
| Mrk 290                 | 91.49  | 47.95 | 58.73  | 18.31 | 17.94  | 99.64   | 4.07     |
| Mrk 421                 | 179.83 | 65.03 | 35.45  | 4.65  | 4.63   | 61.33   | 9.91     |
| Mrk 501                 | 63.60  | 38.86 | 59.23  | 7.36  | 34.80  | 163.34  | 20.28    |
| Mrk 509                 | 35.97  | -29.86 | 71.08  | 14.51 | 21.38  | 142.06  | 20.64    |
| Mrk 841                 | 11.21  | 54.63 | 642.82 | 459.45 | 3114.76 | 8954.72 | 601.84 |
| NGC 3783                | 287.46 | 22.95 | 54.25  | 12.14 | 11.99  | 87.52   | 14.34    |
| NGC 4593                | 297.48 | 57.40 | 93.64  | 63.15 | 353.18 | 1272.36 | 84.94    |
| NGC 5548                | 31.96  | 70.50 | 12.05  | 7.43  | 7.43   | 31.72   | 2.67     |
| NGC 7469                | 83.10  | -45.47 | 46.73  | 23.08 | 7.64   | 117.31  | 38.90    |
| PG1116+215/Ton 1388     | 223.36 | 68.21 | 17.42  | 12.76 | 45.48  | 130.38  | 4.41     |
| PG1211+143              | 267.55 | 74.32 | 633.19 | 479.56 | 2594.25 | 7574.04 | 586.36 |
| PKS 0558-504            | 257.96 | -28.57 | 121.15 | 13.22 | 12.31  | 251.20  | 101.15   |
| PKS2 005-489            | 350.37 | -32.60 | 194.76 | 21.76 | 251.38 | 962.92  | 153.26   |
| PKS 2155-304            | 17.73  | -52.25 | 68.09  | 15.87 | 15.74  | 178.67  | 47.30    |
| H/E1821+643             | 94.00  | 27.42 | 486.85 | 338.37 | 5414.13 | 14216.96 | 468.26  |