Exploring the dispersion measure of the Milky Way halo

Laura C. Keating1,* and Ue-Li Pen1,2,3,4,5

1 Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H8, Canada
2 Canadian Institute for Advanced Research, CIFAR Program in Gravitation and Cosmology, Toronto, ON M5G 1Z8, Canada
3 Dunlap Institute for Astronomy & Astrophysics, University of Toronto, AB 120-50 St. George Street, Toronto, ON M5S 3H4, Canada
4 Perimeter Institute of Theoretical Physics, 31 Caroline Street North, Waterloo, ON N2L 2Y5, Canada
5 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Fast radio bursts offer the opportunity to place new constraints on the mass and density profile of hot and ionized gas in galactic haloes. We test here the X-ray emission and dispersion measure predicted by different gas profiles for the halo of the Milky Way. We examine a range of models, including entropy stability conditions and external pressure continuity. We find that incorporating constraints from X-ray observations leads to favouring dispersion measures on the lower end of the range given by these models. We show that the dispersion measure of the Milky Way halo could be less than 10 cm$^{-3}$ pc in the most extreme model we consider, which is based on constraints from Ovii absorption lines. However, the models allowed by the soft X-ray constraints span more than an order of magnitude in dispersion measures. Additional information on the distribution of gas in the Milky Way halo could be obtained from the signature of a dipole in the dispersion measure of fast radio bursts across the sky, but this will be a small effect for most cases.

Key words: Galaxy: halo – X-rays: diffuse background

1 INTRODUCTION

As fast radio bursts (FRBs) propagate through ionized gas, they interact with free electrons which cause the signal to disperse; that is, a frequency-dependent shift in the group velocity of the wave is observed. The dispersion measure (DM) of a FRB is therefore a probe of the integrated electron density along the line of sight. FRBs have been confirmed to have an extragalactic origin, due to the identification of host galaxies (e.g., Tendulkar et al. 2017; Mahony et al. 2018) as well as statistical arguments based on clustering redshifts (Li et al. 2019). FRBs have been confirmed to have an extragalactic origin, due to the identification of host galaxies (e.g., Tendulkar et al. 2017; Mahony et al. 2018) as well as statistical arguments based on clustering redshifts (Li et al. 2019). Their DMs will therefore have contributions from both the interstellar medium (ISM) and circumgalactic gas of the host galaxy and the Milky Way, as well as intergalactic gas and intervening haloes (see Prochaska & Zheng 2019, hereafter PZ19, for a comprehensive review).

An intriguing possibility is that FRBs may shed light on the “missing baryon problem”, as if there is a significant reservoir of hot, ionized circumgalactic baryons in galactic haloes then this will show up through its contribution to the DM (McQuinn 2014; Muñoz & Loeb 2018). Additional constraints from the rotation measure and pulse widths are also possible (Prochaska et al. 2019), and indeed hint that the circumgalactic medium (CGM) may be more diffuse than suggested by other works (Cantalupo et al. 2014; Lan & Fukugita 2017). If the missing baryons do exist in hot gas ($T \gtrsim 10^6$ K) in the CGM of galaxies, they should be detectable in their soft X-ray emission (Anderson & Bregman 2010; Anderson et al. 2013). In our Galaxy, there are constraints from the homogeneous component of the soft X-ray background (Hasinger et al. 1993) or contributions to X-ray emission from a hot halo component (Henley & Shelton 2013). By modelling this emission, it is possible to constrain the distribution of gas in the CGM of the Milky Way (Pen 1999; Fang et al. 2013) and see what fraction of the missing baryons may lie in the hot CGM.

The rotation curve of many galaxies, including the Milky Way, is observed to be flat out to tens of kpcs, corresponding to an isothermal mass profile. If the gas in these halos traced the dark matter at the cosmic baryon fraction, the DMs of known, localized FRBs would be much higher than observed. The standard resolution is to invoke the expected feedback processes to reduce the column of gas between the Sun and the edge of the Milky Way halo. One might expect this to result in a broad allowed range of halo DMs that can be very small, and bounded from above by observational constraints, including FRB DMs, X-ray background, hydrostatic equilibrium, and external pressure bal-
Figure 1. Top: Electron number density as a function of radius for a halo with $M_{\text{halo}} = 3.5 \times 10^{12} M_{\odot}$. We show two cases for the Pen (1999) model: one where the core radius is chosen to match the upper limit on the 1 keV homogeneous background as discussed in section 3 (blue line) and one where the core radius is equal to the virial radius of the halo (orange line). Middle: Temperature as a function of radius. We show two cases for the temperature of the NFW profile: constant entropy (dotted line) and constant temperature (solid line). Bottom: Enclosed gas mass as a function of radius. The horizontal grey dashed line shows the cosmological gas fraction of the halo.

ance. It is perhaps surprising that a narrow range has been suggested (e.g., PZ19). We critically examine the constraints in this broader context here.

In this Letter, we explore the allowed range of values for the DM due to the ionized gas in the halo of the Milky Way, incorporating constraints from soft X-ray emission. In particular, we revisit some of the halo density profiles presented in PZ19, as well as including some additional profiles. We begin by describing these models in section 2. We compute their expected X-ray emission in section 3 and their DM in section 4. Finally, we present our conclusions in section 5.

2 HALO GAS DENSITY PROFILES

It is instructive to first consider simple limits. The Milky Way infall radius is about 2 Mpc/$h$, which collapses by a factor of 9 into the virial radius of 220 kpc/$h$ (for a halo with a constant rotation velocity of 220 km s$^{-1}$). The fiducial DM through the halo would be 0.07 cm$^{-3}$ pc if the gas stayed at constant density. For a constant rotation velocity, the mass distribution is isothermal with $\rho \propto 1/r^2$. In ideal adiabatic collapse simulations, gas traces dark matter at or near the cosmic ratio down to ten per cent of the virial radius (Frenk et al. 1999) and half the cosmic value at small radii. This would result in a DM of over $350$ cm$^{-3}$ pc as seen from the solar radius, which is at odds with numerous observations, including FRB DMs and the X-ray background. Thus, all models invoke some form of feedback to reduce the amount of gas near the solar radius. One might expect that any value would then be allowed, depending on the assumed feedback process. It seems perhaps surprising that PZ19 find a narrow range of DM. We attribute this to their assumption that gas cannot leave the fiducial halo boundary. In this case, with infinite heat injection, the gas becomes distributed uniformly within the virial radius, and the DM seen from the centre is $47$ cm$^{-3}$ pc; close to the lower value considered by PZ19.

In this Letter, we will open the scenarios to allow gas escape, and impose pressure equilibrium and convective stability. Perhaps not surprisingly, the allowed range increases substantially. We revisit here several of the halo gas profiles presented in PZ19\(^1\). Several of these models are based on Navarro, Frenk & White (1997) (NFW) profile, derived by fitting to density profiles of haloes in dark matter simulations. Mathews & Prochaska (2017) presented a modified version of the NFW profile (mNFW), motivated by the impact that baryonic feedback effects would have on the gas density profile and observations of circumgalactic Oiv emission lines. The mNFW profile introduces two additional parameters ($y_0$ and $\alpha$) and is defined as

$$\rho(r) = \rho_0 \frac{R_{200}}{r} \left( \frac{r}{R_{200}} \right)^{\alpha} \left( 1 + \frac{r}{R_{200}} \right)^{-y_0 - \alpha + 1} ,$$

where $\rho(r)$ is the density at radius $r$, $\rho_0$ is a characteristic density and $y$ and $\alpha$ is the halo concentration $c$ and $R_{200}$ is the virial radius. We assume that $c = 7.7$ here. The case with $y_0 = 1$ and $\alpha = 0$ corresponds to the original NFW profile. As in PZ19, we consider here mNFW profiles with $y_0 = 2$ and $y_0 = 4$, and keep $\alpha = 2$ in both cases.

The Maller & Bullock (2004) gas density profile is motivated by the assumption that the halo gas is adiabatic and in hydrostatic equilibrium. Its density profile is defined as

$$\rho(r) = \rho_c \left( 1 + \frac{3.7}{\gamma} \ln(1 + y) - \frac{3.7}{C_\gamma} \ln(1 + C_\gamma) \right)^{\frac{3}{2}} ,$$

where $\rho_c$ is a normalisation constant which is determined by the gas mass of the halo, $\gamma$ is defined as above, $C_\gamma = c R_{200}^{-1}$ and $R_c$ is the cooling radius, which we set to 147 kpc.

We also investigate some profiles that were not examined in PZ19. This includes a constraint on the shape of the gas density profile determined from O\emissionline vii absorption in Miller & Bregman (2013) (see also Miller & Bregman 2015, for similar constraints using O\emissionline vii and O\emissionline viii emission lines). They fit the data with a spherical density model of the form

$$n(r) = n_0 \left( 1 + \left( \frac{r}{r_c} \right)^2 \right)^{-3/2} ,$$

with best-fit parameters $n_0 = 0.46$ cm$^{-3}$, $r_c = 0.35$ kpc and $\beta = 0.71$. They also further add a ambient density component $n_a = 10^{-5}$ cm$^{-3}$ at all radii, based on ram-pressure stripping of dwarf spherioidals (Blitz & Robishaw 2000).

\(^1\) which they have made available on https://github.com/FRBs

MNRS 000, 1–5 (xxxx)
We also investigate the pNFW model of Voit (2019). This model assumes a constant circular velocity at small radii, and the velocity profile of a NFW halo at larger radii and accounts for the precipitation of cold clouds from the hot halo gas. The density is determined assuming their fitting function

$$n(r) = \left\{ \begin{array}{ll}
\left( r_1 \frac{r}{1 \text{ kpc}} \right)^{-2} & \text{if } r < r_c \\
\left( r_2 \frac{r}{100 \text{ kpc}} \right)^{-2} & \text{if } r \geq r_c
\end{array} \right. ,$$

where $n_1$, $n_2$, $\xi_1$ and $\xi_2$ are interpolated from the coefficients they tabulate as a function of halo mass.

Finally, we consider the entropy-floor singular isothermal sphere model of Pen (1999), which was motivated to match the observed limits on the soft X-ray background and invokes baryonic feedback to create a shallower slope in the inner part of the halo gas density profile. This density profile is defined as

$$\rho(r) = \frac{f_{\text{NFW}}}{4\pi G} \left( \frac{r}{r_c} \right)^{\frac{1}{2}} \left( 1 + \frac{12}{25} \ln \left( \frac{r}{r_c} \right) \right)^{3/2}, \quad r > r_c,$$

Examples of these density profiles are shown in left panel of Figure 1. Here, we have assumed that the mass of the Milky Way can be calculated from an extrapolation of the circular velocity at the radius of the Sun (as assumed in Pen 1999). This results in a mass of $M_{\text{MW halo}} = 3.5 \times 10^{12} M_\odot$, somewhat higher than most estimates of the mass of the Milky Way halo, which at the highest end are about $M_{\text{MW halo}} \sim 2.5 \times 10^{12} M_\odot$ (Li & White 2008; Boylan-Kolchin et al. 2010). We use this high halo mass as an upper limit on the gas mass of the Milky Way halo, and also examine a lower mass halo with the properties assumed in PZ19 ($M_{\text{MW halo}} = 1.5 \times 10^{12} M_\odot$) in sections 3 and 4. We also note that some estimates for the Milky Way halo mass can be as low as $M_{\text{MW halo}} \sim 0.5 \times 10^{12} M_\odot$ (Gibbons et al. 2014), which would lead to even lower gas masses (and hence lower dispersion measures) than the models presented here.

In the middle panel of Figure 1, we show the temperature as a function of radius we assume for each of these models. For the NFW profile, we take two cases: first, assuming that the halo is isothermal with a temperature given by the virial temperature (black solid line) and second, that the entropy inside the halo is constant (black dashed line). The Pen (1999) model assumes that the entropy is constant inside the core radius and that the gas is isothermal and equal to the virial temperature otherwise. For the Voit (2019) model, we calculate the entropy using another fitting function that they provide. We assume constant entropy inside the halo for all other models, with the constraint that the temperature should reach the virial temperature at the virial radius. For the mNFW models, we note that this assumption leads to a non-monotonic temperature profile.

We show the enclosed gas mass as a function of radius for all models in the right panel of Figure 1. All of the models presented in PZ19 assume that the halo gas fraction is 0.75 times the cosmological gas fraction. This means that even though feedback is being invoked as a mechanism for reshaping the density profile, it is not actually expelling any gas from the halo. We note that no assumption for a halo gas fraction is needed in Pen (1999), where the halo gas fraction falls naturally as the core radius is increased. The Voit (2019) profile similarly has a lower enclosed gas mass. The enclosed mass of the Miller & Bregman (2013) model has by far the lowest enclosed mass, although as noted in that work it is consistent with the expected mass of observed high velocity clouds in the Galactic halo (Lehner et al. 2012).

3 X-RAY EMISSION OF THE MILKY WAY HALO

We next compute the X-ray emission predicted from each model, and compare it to limits from the 1 keV soft X-ray background (Hasinger et al. 1993) and estimates of the X-ray surface brightness from the hot halo gas of the Milky Way (Henley & Shelton 2013). We assume this emission is dominated by free-free emission, with a volume emissivity

$$\epsilon_{\text{ff}}^s = 6.8 \times 10^{-38} Z_i^2 n_e n_i T^{-1/2} e^{-h\nu/k_B T} \bar{g} \text{ erg s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}$$

as in Rybicki & Lightman (1986), where $n_e$ and $n_i$ are the number densities of electrons and ions, $Z_i$ is the charge of the ion, $T$ is the temperature, $\nu$ is the frequency of interest and $\bar{g}$ is the mean Gaunt factor (which we set to 1.2). $h_B$ and $k_B$ are the Planck and Boltzmann constants respectively. We assume that the gas is a mixture of ionized hydrogen and helium. As in Pen (1999), we multiply this by an additional factor.
term \( c_Z = \frac{Z}{Z_\odot} \left( \frac{4 \times 10^3}{T_{\text{vir}}} + 1 \right) \) to account for metal cooling (Raymond et al. 1976). Following PZ19, we assume that the halo gas has a metallicity of \( Z = 0.3 Z_\odot \). If the metallicity of halo gas is closer to 0.5 \( Z_\odot \) (Faerman et al. 2017; Qu & Bregman 2018), then our predicted X-ray emission would be correspondingly higher, pushing more models closer to the limits of what is allowed by observations. Similarly, if the gas is somewhat hotter than what is assumed in Figure 1, then this will also boost the associated X-ray emission.

We first compute the X-ray emission at 1 keV and compare with the upper limit of the homogeneous part of the 1 keV background (top row of Figure 2). For the Pen (1999) model, we show cases with a heated core radius that produces X-ray emission at the limit of the observational constraints (0.29 \( R_{200} \) for the more massive halo) or that maximises the X-ray emission (0.14 \( R_{200} \) in the lower mass halo). We also show models with a heated core radius equal to \( R_{200} \), corresponding to a case that maximises the effect of feedback on the CGM of our Galaxy. In the second row of Figure 2, we show the predicted X-ray surface brightness integrated from 0.2 to 2 keV. We note that models which agree with the upper limit of the homogeneous 1 keV background fall to the high end of these observations, perhaps motivating that this limit should be somewhat lower.

We confirm the result of Pen (1999) and Fang et al. (2013) that both the constant temperature and constant entropy versions of the NFW profile dramatically overproduce the X-ray emission of the Milky Way in all but one of the cases we consider, the isothermal NFW in the lower mass halo. This has a virial temperature \( T_{\text{vir}} = 6.5 \times 10^5 \) K, not high enough to produce substantial X-ray emission. Several of the other density profiles we investigate also overproduce the X-ray emission compared to observations, highlighting that this is a useful probe of the CGM. In particular we note that the fiducial halo model of PZ19 (a mNFW profile with \( y_0 = 2 \) and \( \alpha = 2 \)) is inconsistent with the X-ray observations, overproducing emission with respect to both the limits from the homogeneous component of the soft X-ray background and the estimates from individual sightlines.

## 4 Dispersion Measure of the Milky Way Halo

We compute the DM predicted for each model, defined as \( \text{DM} = \int n_e \, dl \). We compute the DM as a function of radius (starting at the solar radius) out to the virial radius of our Galaxy (Figure 3). The DMs vary by almost two orders of magnitude depending on the gas density profile assumed, although some of these can already be ruled out based on their X-ray emission (section 3). Among the models that are compatible with the observations of Henley & Shelton (2013), the maximum DM is 55 cm\(^{-3}\) pc. The Miller & Bregman (2013) model and the Pen (1999) model assuming a heated core radius equal to the virial radius predict a DM lower than the estimate of 30 cm\(^{-3}\) pc commonly used for the Milky Way halo (Dolag et al. 2015; Shell & Danforth 2018). This is also the case in the Voit (2019) model for the lower mass halo we consider. In the most extreme gas profile we consider (the Miller & Bregman 2013 profile), we find that the DM could be as low as 6 cm\(^{-3}\) pc in the lower mass halo. This is substantially lower than the DM measured for pulsars in the Large Magellanic Cloud (LMC), but that could be due to the ISM contribution to the DM which we have not included here. There is therefore considerable variation between models, and the DM of the Milky Way halo is perhaps not as well known as claimed in some works. We note also that the FRB with the lowest DM currently measured already begins to rule out some models after subtracting the ISM component, even though the DM constraint we quote will still contain contributions from intergalactic gas and the FRB host, as well as the Milky Way halo.

We next investigate the dipole distortions of the Milky Way DM, i.e., the fact that it will be higher when looking towards the Galactic centre (Figure 4). We find that, for most of the models, this effect is small with the DM varying by only tens of per cent among different sightlines. For the NFW, Voit (2019) and Miller & Bregman (2013) profiles, this effect is more extreme with the DM increasing by a factor of a few in sightlines that are close to the centre of the halo. This effect will likely be difficult to tease out, however, due to the fact that the CGM is likely more complicated than the smooth density profiles we consider here and that in the AGN.

**Figure 3.** The dispersion measure as a function of radius starting at the radius of the Sun and looking away from the Galactic centre for the two halo masses we consider (top panel: \( M_{\text{MW/halo}} = 3.5 \times 10^{12} M_\odot \), bottom panel: \( M_{\text{MW/halo}} = 1.5 \times 10^{12} M_\odot \)). The horizontal grey dotted line is the DM estimated from O\textsc{iv} absorption (Shull & Danforth 2018). The circle is the median DM from pulsars in the LMC (Ridley et al. 2013), and the errorbars show the complete range of DMs. The square is the halo DM at the distance of the LMC from PZ19. The grey shaded region shows the lowest DM currently measured for a FRB, after the contribution from the Milky Way ISM has been subtracted using the Yao et al. (2017) model (CHIME/FRB Collaboration et al. 2019).
centre of the halo there will also be contribution from the ISM, although this has been extensively modelled (Cordes & Lazio 2002, 2003; Gaensler et al. 2008; Yao et al. 2017).

5 CONCLUSIONS

We have presented here an investigation into the range of possibilities for the DM of the Milky Way halo. Previous works have claimed that there is only a small uncertainty associated with this quantity. We test a range of models of the gas density profile of the Milky Way CGM against their predicted soft X-ray emission, and find that some are disfavoured by the data. However, even among the allowed models, the predicted values for the halo DM differ by more than an order of magnitude. We note that additional constraints can be obtained from absorption line studies of the Galactic halo and the CGM of other Milky Way-like galaxies, as discussed in detail in PZ19.

As well as the contribution to the DM from the Milky Way CGM, there will of course also be contribution from the host halo of the FRB and from gas in intervening haloes along the line of sight. If the CGM of halos is as diffuse as some models considered here, then this will have implications for the scatter in DM along different sightlines. A sample of FRBs at known redshifts could start to place interesting constraints on allowed gas profiles (McQuinn 2014). As more FRBs are localised to host galaxies, they will open an exciting new avenue for probing the CGM of the Milky Way and other galaxies, complementary to absorption and emission line studies.

REFERENCES

Anderson M. E., Bregman J. N., 2010, ApJ, 714, 320
Anderson M. E., Bregman J. N., Dai X., 2013, ApJ, 762, 106
Blitz L., Robishaw T., 2000, ApJ, 541, 675
Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., 2010, MNRAS, 406, 896
CHIME/FRB Collaboration et al., 2019, ApJ, 885, L24
Cantalupo S., Arrigoni-Battaia F., Prochaska J. X., Hennawi J. F., Madau P., 2014, Nature, 506, 63
Cordes J. M., Lazio T. J. W., 2002, arXiv e-prints, pp astro-ph/0207156
Cordes J. M., Lazio T. J. W., 2003, arXiv e-prints, pp astro-ph/0301508
Dolag K., Gaensler B. M., Beck A. M., Beck M. C., 2015, MNRAS, 451, 4277
Faereman Y., Sternberg A., McKee C. F., 2017, ApJ, 835, 52
Fang T., Bullock J., Boylan-Kolchin M., 2013, ApJ, 762, 20
Frenk C. S., et al., 1999, ApJ, 525, 554
Gaensler B. M., Madsen G. J., Chatterjee S., Mao S. A., 2008, Publ. Astron. Soc. Australia, 25, 184
Gibbons S. L. J., Belokurov V., Evans N. W., 2014, MNRAS, 445, 3788
Hasinger G., Burg R., Giacconi R., Hartner G., Schmidt M., Trumper J., Zamorani G., 1993, A&A, 275, 1
Henley D. B., Shelton R. L., 2013, ApJ, 773, 92
Lan T.-W., Fukugita M., 2017, ApJ, 850, 156
Lehner N., Howk J. C., Thom C., Fox A. J., Tumlinson J., Tripp T. M., Meiring J. D., 2012, MNRAS, 424, 2896
Li Y.-S., White S. D. M., 2008, MNRAS, 384, 1459
Li D., Yalinewich A., Breysse P. C., 2019, arXiv e-prints, p. arXiv:1902.10120
Mahony E. K., et al., 2018, ApJ, 867, L10
Maller A. H., Bullock J. S., 2004, MNRAS, 355, 694
Mathews W. G., Prochaska J. X., 2017, ApJ, 846, L24
McQuinn M., 2014, ApJ, 780, L33
Miller M. J., Bregman J. N., 2013, ApJ, 770, 118
Miller M. J., Bregman J. N., 2015, ApJ, 800, 14
Muñoz J. B., Loeb A., 2018, Phys. Rev. D, 98, 103518
Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
Pen U.-L., 1999, ApJ, 510, L1
Prochaska J. X., Zheng Y., 2019, MNRAS, 485, 648
Prochaska J. X., et al., 2019, arXiv e-prints, p. arXiv:1909.11681
Qu Z., Bregman J. N., 2018, ApJ, 856, 5
Raymond J. C., Cox D. P., Smith B. W., 1977, ApJ, 204, 290
Ridley J. P., Crawford F., Lorimer D. R., Bailey S. R., Madden J. H., Anella R., Chennamangalam J., 2013, MNRAS, 433, 138
Rybicki G. B., Lightman A. P., 1986, Radiative Processes in Astrophysics. John Wiley & Sons
Shull J. M., Danforth C. W., 2018, ApJ, 852, L11
Tendulkar S. P., et al., 2017, ApJ, 834, L7
Voit G. M., 2019, ApJ, 880, L30
Yao J. M., Manchester R. N., Wang N., 2017, ApJ, 835, 29