The Warm Gaseous Disk and the Anisotropic Circumgalactic Medium of the Milky Way

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Abstract

Warm (log T ≈ 5) gas is an important gaseous component in the galaxy baryonic cycle, which is important for understanding both gas accretion and galactic feedback processes. We built a two-dimensional disk–circumgalactic medium (CGM) model to study the warm gas distribution of the Milky Way (MW) using the absorption-line surveys of Si IV and O VI. In this model, the disk component of both ions has the same density profile \( n(r, z) = n_0 \exp(-|z|/\z_0)\exp(-r/r_0) \) with a scale height of \( \z_0 = 2.6 \pm 0.4 \) kpc and a scale length of \( r_0 = 6.1 \pm 1.2 \) kpc. For this disk component, we calculate the warm gas mass of \( \log(M/M_\odot) = (7.6 \pm 0.2) - \log(Z/Z_\odot) \). The similar disk density profiles and total masses of the Si IV- and O VI-bearing gas set constraints on the ionization mechanisms. We suggest that the warm gas disk might be dominated by the Galactic fountain mechanism, which ejects and recycles gas to set both the scale height and the scale length of the warm gas disk. The CGM component in our model has a dependence on Galactic latitude, with a higher column density along the direction perpendicular to the Galactic plane (b = 90°) than along the radial direction (b = 0°). The column density difference between these two directions is 0.82 ± 0.32 dex at 6.3r for both ions. This difference may be due to either the enrichment of Galactic feedback to the entire CGM or an additional interaction layer between the warm gas disk and the CGM; existing data cannot distinguish between these two scenarios. If this higher column density at b = 90° is for the entire CGM, the total warm CGM mass is \( \log(M/M_\odot) \approx (9.5 - 9.8) - \log(Z/0.5 Z_\odot) \) within the MW virial radius of 250 kpc.

Key words: Galaxy: disk – Galaxy: halo – quasars: absorption lines

1. Introduction

Gaseous baryons in galaxies can be found in both gaseous disks (the interstellar medium; Dickey & Lockman 1990) and gaseous halos (the circumgalactic medium, CGM; Putman et al. 2012; Tumlinson et al. 2017). Gaseous disks are roughly coplanar with the galaxy stellar disks, whereas the CGM surrounds the stellar disks. H I 21 cm line surveys or ultraviolet (UV) observations reveal that gaseous disks can extend beyond the stellar disks (up to 30–50 kpc along the major axis) with masses from \( 10^7 M_\odot \) to \( \lesssim 10^{10} M_\odot \) for low-redshift galaxies (z \( \lesssim 0.2 \); Oosterloo et al. 2007; Bregman et al. 2018). With the statistical assembly of quasar–galaxy pairs in UV absorption lines, the CGM can be detected out to large radii (>50 kpc) and contribute a large amount of baryonic material (\( \gtrsim 10^{10} M_\odot \)) for galaxies at z \( \lesssim 0.5 \) (Stocke et al. 2013; Werk et al. 2014; Lehner et al. 2015; Keeney et al. 2017).

The existence of these gaseous components is important for galaxy evolution because they mediate both accretion and feedback processes (Mo et al. 2010). For \( L \gtrsim L^* \) galaxies, the CGM is normally volume-filled by warm-hot gas (log \( T \approx 5–7 \)) together with discrete cool gas clouds (log \( T \approx 4–5 \)), which is mainly shock-heated by gas accreted from the intergalactic medium (IGM) and altered by feedback processes from host galaxies (Cen & Ostriker 2006). The existence of the CGM could prevent direct accretion from the IGM; instead, it provides cooling materials from itself through thermal or gravitational instabilities (Kereš et al. 2009). These cooling flows from the CGM supplement the gaseous disk and sustain the star formation activities in the stellar disk (Lehner & Howk 2011; Li et al. 2014; Borthakur et al. 2015; Qu & Bregman 2018). In turn, the stellar and active galactic nucleus (AGN) feedback could enrich the CGM by ejecting gas, energy, and metals (Borthakur et al. 2013; Fielding et al. 2017; Oppenheimer et al. 2018).

The warm (log \( T \approx 5 \)) gas is of special importance, as it is at transitional temperatures (the peak of the radiative cooling curve). In this temperature range, the gas could be the interaction layer between the cool gas and the warm-hot gas. These interactions are mostly associated with galactic feedback (e.g., outflows) or gas accretion onto the disk (e.g., accretion shocks). Therefore, the distribution of the warm gas is crucial to investigate these fundamental processes. Observationally, the warm gas distribution could be divided into two components: the warm gas disk and the warm CGM. The warm gas disk has been studied for both other galaxies (Boettcher et al. 2016; Zheng et al. 2017; Qu et al. 2019) and the Milky Way (MW; Howk et al. 2002; Finkbeiner 2003; Savage et al. 2003; Wakker et al. 2012). For other galaxies, the warm gas disk has been detected in various observations. Direct imaging of nearby edge-on galaxies has detected the warm gas disk at radii of \( \approx 1–10 \) kpc in the X-ray band, UV band, and nebula emission lines (Rand et al. 2008; Li & Wang 2013; Boettcher et al. 2016; Hodges-Kluck et al. 2016). However, for the warm CGM, these observations are limited at larger radii (>50 kpc), due to the current instrument limitations and the low surface brightness of the diffuse ionized gas. An alternative is to use UV absorption lines against the continua of background AGN/stellar objects to detect gas with column densities as low as \( \approx 10^{12} \) cm \(^{-2} \) (Tumlinson et al. 2017 and references therein). The warm gas is traced by intermediate to high ionization state UV ions, such as Al III, Si IV, C IV, and O VI (Stocke et al. 2013; Werk et al. 2014; Johnson et al. 2015; Lehner et al. 2015; Zheng et al. 2017; Qu et al. 2019). However, extragalactic absorption-line studies are all limited by the sample of available sight lines for individual galaxies.
The MW is a unique target to study the warm gas distribution, with hundreds of sight lines over the sky mapping both the disk and the CGM (Savage et al. 1997; Howk et al. 2002; Wakker et al. 2003, 2012; Savage & Wakker 2009; Lehner & Howk 2011; Lehner et al. 2012; Fox et al. 2014, 2015; Bordoloi et al. 2017; Karim et al. 2018). Previous studies indicated that the warm gas could be discrete kiloparsec-size clouds, which can be detected as either intermediate-velocity clouds (IVCs) or high-velocity clouds (HVCs; Sembach et al. 2003; Wakker et al. 2003, 2012; Fox et al. 2004; Shull et al. 2009; Werk et al. 2019). At large scales, the warm gas distribution in the MW has been modeled as a plane-parallel slab with only a one-dimensional (1D) variation over the vertical direction (perpendicular to the disk) as an exponential function of \( n(z) = n_0 \exp(-|z|/z_0) \), where \( z_0 \) is the scale height (Savage & Wakker 2009 and references therein; hereafter SW09). The scale height of the warm gas disk is measured using column densities against UV-bright stars at different \( z \) heights and AGNs. In this model, the stellar sight lines are used to estimate the ion density at the midplane of the disk. Combined with the sight lines toward AGNs (determining the maximum projected column density), the scale heights of the plane-parallel slab model are obtained for various ions, where no CGM component is considered. However, more recent observations reveal that the CGM also contributes to the column densities of the intermediate to high ionization state ions measured in the AGN sight lines (Werk et al. 2014; Johnson et al. 2015; Lehner et al. 2015; Stocke et al. 2017; Zahedy et al. 2019). As pointed out by Zheng et al. (2019, hereafter Zheng19), the MW CGM contributes a significant amount of column density to the Si IV absorption lines measured with the 132 AGN sight lines obtained by the Cosmic Origins Spectrograph (COS; Green et al. 2012) on the Hubble Space Telescope (HST). They demonstrated that the warm gas in the MW, as observed with all-sky AGN sight lines, should be modeled with a two-component model (i.e., a disk component and a CGM component). In their two-component model, the disk component follows the 1D plane-parallel slab model that SW09 adopted, and the halo component is modeled as a uniform global background.

This paper builds on the two-component model of Zheng19 to develop a disk–CGM model that accounts for both the radial and vertical density profiles of the disk. This model is applied to Si IV and O VI, which are typical ions tracing the transitional temperature gas (Savage et al. 1997; Wakker et al. 2012). In Section 2, we summarize the data used in this study, which include column density measurements from MW stellar sight lines by SW09 and from all-sky AGN sight lines by Savage et al. (2003, hereafter Savage03) and Zheng19. We introduce our model in Section 3 and show that the inclusion of the disk radial profile can alleviate the disagreement between the plane-parallel slab model based on the stellar sample (SW09) and the two-component model based on the AGN sample (Zheng19). The anisotropic CGM model is also introduced in Section 3, showing that the MW is likely to have a warm CGM with anisotropic column density distribution. In Section 4, we discuss the implication of this work on the warm gas disk (Section 4.2), the warm CGM of the MW (Section 4.3), and the north–south (NS) asymmetry of the MW warm gas absorption features (Section 4.4). The key results are summarized in Section 5.

### 2. Data

At the temperature of \( \approx 10^{5} K \), the transitional gas can be traced by intermediate to high ionization state ions, such as Si IV with ionization potential of 33.5–45.1 eV, C IV (47.9–64.5 eV), N V (77.5–97.9 eV), or O VI (113.9–138.1 eV). These ions are detectable in absorption against the continua of background UV-bright stars or AGNs. For observations of the MW warm gas disk and the CGM, the stellar sight lines are normally at low Galactic latitudes \((|b| \lesssim 5^{\circ}; \text{SW09})\), whereas the AGN sight lines are at high Galactic latitudes \((|b| \gtrsim 30^{\circ}; \text{Savage03; Zheng19})\). The stellar sight lines are employed to measure the midplane density of the disk, while the AGN sight lines can trace the largescale variation of the disk (e.g., scale height of the disk) and the CGM. Therefore, these two samples are equally important to constrain both the gaseous disk shape and the CGM contribution. We only consider the ions that have high signal-to-noise ratio, \( \gtrsim 15 \), samples for both disk stars and AGNs of sample sizes \( N \gtrsim 100 \).

Based on this criterion, Si IV and O VI are the two ions that have both stellar sight lines from SW09 and AGN sight lines from Savage03 and Zheng19. In this study, we do not consider C IV, because the current largest AGN sample \((N \approx 30–40)\) from Wakker et al. (2012) does not have sufficient sight lines to obtain a good fitting result. All three samples (Savage03; SW09; Zheng19) used have similar velocity ranges \(|v| \lesssim 100 \text{ km s}^{-1}\) for the measurement of the column density, so we only study the low- to intermediate-velocity gas of the MW (without HVCs, \(|v| \gtrsim 100 \text{ km s}^{-1}\). Zheng et al. (2015) showed that a significant amount of the CGM is at low to intermediate velocities using a MW-mass hydrodynamic simulation (Joung et al. 2012), so we expect that we could detect both the warm gas disk and the CGM using these samples.

For the stellar sample, SW09 summarized the Far-Ultraviolet Spectroscopic Explorer (FUSE), IUE, and Copernicus sight lines toward the 109 MW stars, 25 AGNs, and six LMC/SMC stars with good measurements \((\sigma_{N} < 0.4 \text{ dex})\) or limits of Si IV and O VI. This sample is mainly based on the Galactic O VI surveys, such as Bowen et al. (2008), for low-latitude disk stars and Zsargó et al. (2003) for halo stars. Compared to the Bowen et al. (2008) sample, SW09 excluded sight lines with large uncertainties of O VI and other transitional ions (e.g., C IV, Si IV; Savage et al. 2001). The excluded sight lines are mainly stellar sight lines within 1 kpc. Because SW09 also included sight lines toward halo stars at \(|z| > 1 \text{ kpc}\), this sample is better to constrain the scale height of the disk component. We exclude sight lines that might be contaminated by foreground H II regions as marked by SW09. Aside from the Galactic stellar sample, SW09 also included six stars in LMC/SMC, which are not used in our analyses. This is because one needs to assume the radial density profile of the MW CGM to model the ion column densities from stars at the distance of 50–60 kpc, which is highly uncertain. Therefore, we do not implement this variation in our model and omit the sight lines toward LMC/SMC stars. The final stellar sample used in our analyses is composed of 77 sight lines, 75 of which have good column density \((\log N)\) measurements or limits for Si IV, and all of them have good log \( N \) values or limits for O VI (Table 1).

For the AGN sample, we adopt two data sets. We make use of the Si IV measurements from the COS-GAL sample (Zheng19), which is based on the Hubble Spectroscopic Legacy Archive (Peeples et al. 2017). Moreover, we retrieve the O VI measurements from the FUSE observations analyzed...
by Savage03. We do not include the AGN sample in SW09 because it has a large overlap with the Zheng19 sample (18/25) and the Savage03 sample (22/25). The final AGN sample includes 130 sight lines for SiIV and 101 sight lines for OVI (Table 1).

### 3. Models and Results

#### 3.1. Previous Models

Previously, the warm gas disk (i.e., traced by Si IV and O VI) of the MW has been modeled as a 1D plane-parallel slab model (Jenkins 1978; Bowen et al. 2008; SW09). The model only has one-dimensional variation: the density distribution of the warm gas over the disk height $z$ as an exponential function of $n(z) = n_0 \exp(-|z|/z_0)$, where $n_0$ is the ion density at the midplane and $z_0$ is the scale height. The current stellar sight lines are normally close to the Sun with a distance of $d \lesssim 2$ kpc, which implies that the average ion densities traced by these sight lines do not vary significantly at large scales. Therefore, the stellar sight lines mainly determine the average density of the midplane around the solar system ($n_z$). For the AGN sight lines, both the disk and the CGM are detected to show the large-scale variation. Based on the AGN sight lines, one could obtain the maximum projected column density along the $z$-direction $(N \sin|b|)$ for the disk component, because in the plane-parallel slab model, the CGM contribution is ignored. Combining these two measurements, the scale height $z_0$ in the plane-parallel slab model is derived as $N \sin|b|/n_\odot$ around the solar neighborhood.

This model works well for the sample dominated by stellar sight lines, such as SW09, which has $\approx100$ stellar sight lines and $\approx20$ AGN sight lines. However, this model might have two problems as more and more AGN sight lines are obtained by HST/COS. First, for sight lines toward AGNs, the contribution from the MW CGM is not considered, which has been shown as an important component for low-redshift galaxies ($z \lesssim 0.5$; e.g., Stocke et al. 2013; Werk et al. 2014; Johnson et al. 2015). Second, the AGN sight lines could trace the large-scale variation of the disk in both the vertical and radial directions, so the plane-parallel slab model might lead to divergence from observations.

The first problem is partially solved in Zheng19 by introducing an isotropic CGM component ($N_{\text{CGM}}$) into the plane-parallel slab model; their model is referred to as the two-component disk–CGM model hereafter. They applied the two-component disk–CGM model to fit the SiIV column density distribution measured along 130 AGN sight lines across the Galactic sky and found a significant contribution of the MW CGM of $\log N_{\text{CGM}} \approx 13.53$. The Zheng19 analyses provide the first statistical evidence that the MW hosts an extended warm CGM. However, in this model, the disk component ($\log N_{\text{disk}} = 12.1$) is different from that of SW09 ($\log N_{\text{disk}} = 13.4$) by more than one order of magnitude. Therefore, there is still a huge gap between the model dominated by stellar sight lines (the plane-parallel slab model; SW09) and the model dominated by AGN sight lines (the two-component disk–CGM model; Zheng19). In the following, we introduce a two-dimensional (2D) disk–CGM model with a disk radial profile that alleviates the tension between the flat-slab model by SW09 and the two-component disk–CGM model by Zheng19 in studying the warm gas in the MW.

### 3.2. The 2D Disk–CGM Model

We improve the previous models by introducing a 2D disk into the two-component disk–CGM model of Zheng19. In this model, we consider the number density distribution of the disk component, which is a 2D distribution ($n_{\text{disk}}(r, z)$) depending on the radius ($r$) from the Galactic center (GC) and the $z$-height above and below the Galactic plane. For a given sight line at a given distance ($l, b, d$), we can calculate the column density contribution from the disk by integrating the 2D density distribution of the disk component. For the CGM component, we first consider a constant CGM column density over all directions (isotropic $N_{\text{CGM}}$; the same as Zheng19). This CGM component is only applied to the AGN sight lines, while the disk component is calculated for both stellar and AGN sight lines. For a given sight line, the model-predicted column densities are

$$N(l, b, d) = N_{\text{disk}}(l, b, d) + N_{\text{CGM}}$$

where $d_{\text{max}}$ is the maximum distance for the disk component, which is set to be the virial radius of the MW halo ($R_{\text{vir}} = 250$ kpc).

Here, we emphasize that the decomposition of the disk and the CGM component is phenomenological, because we assume that the stellar sight lines do not trace any CGM gas. This is limited by the current sample, which does not have sight lines in the MW halo that trace the radial profile of the MW CGM at large radii, so we cannot calculate the CGM contribution to the column density measurements in the stellar sight lines. However, this assumption is also reasonable with the current sample. For stellar sight lines, most stars are close to the disk midplane center $|z| \lesssim 3$ kpc and are marginally affected by the CGM component. There are only three stars that have $|z| > 3$ kpc, giving rise to a tiny effect on the fitting results.

For the 2D disk component, the radial and vertical profiles are assumed to be independent of each other, so the ion number density distribution in the disk is

$$n(r, z) = n_0 f_r(r) f_z(z),$$

where $f_r(r)$ and $f_z(z)$ are the profile functions in the radial and vertical directions. For $f_z(z)$, we adopt the same exponential profile, $f_z(z) = \exp(-|z|/z_0)$, as the plane-parallel slab model (SW09). We also assume the radial profile to be exponential as $f_r(r) = \exp(-r/r_0)$, where $r_0$ is the scale length. Both of the

| Ion | $N_{\text{stat}}$ | $N_{\text{AGN}}$ | $\sigma$ | References |
|-----|-----------------|-----------------|---------|------------|
| Si IV | 49 | 13 | 13 | ... | 0.30 | SW09 |
| ... | ... | ... | ... | ... | 0.13 | Zheng19 |
| O VI | 73 | 0 | 4 | ... | 0.23 | SW09 |
| ... | 93 | 0 | 8 | ... | 0.15 | Savage03 |

Notes.

* These two columns are the number of sight lines from the stellar or AGN sample, respectively. In each column, the three numbers are for sight lines with column density measurements, lower limits, and upper limits, respectively.

* $\sigma$ is the patchiness parameter (defined in Section 3.2), which represents the intrinsic scatter of the column density measurements in each sample. The patchiness parameter is derived to reduce the reduced $\chi^2$ value to 1 for each sample individually.

**Table 1**

Sample

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radial and vertical exponential profiles are empirical as inferred from the H I disk and the stellar disk (Kalberla & Dedes 2008; Bovy & Rix 2013). It is possible that the warm gas disk follows a different density distribution, because the warm gas disk is more extensive and affected by Galactic feedback. Therefore, in the following analyses, we also consider the Gaussian function \( f(x) = \exp\left(-\frac{(x-x_0)^2}{2\sigma^2}\right) \) for both \( f(x) \) and \( f(z) \) to test whether the shape of the warm gas disk can be distinguished from the observations. In total, there are four phenomenological models for our disk density profiles: \( R_1Z_0 \) (exponential radial and vertical profiles), \( R_GZ_E \) (Gaussian radial profile and exponential vertical profile), \( R_EZ_G \) (Exponential radial profile and Gaussian vertical profile), and \( R_GZ_G \) (Gaussian radial and vertical profiles). In these models, the solar system is placed at \( r_0 = 8.5 \) kpc (Ghez et al. 2008) and \( z_0 = 0 \) kpc.

We apply these models to the column density measurements of Si IV and O VI (Savage03; SW09; Zheng19) and obtain the best parameters using the minimum \( \chi^2 \) estimation. In our fittings, we include the lower or upper limits of the log \( N_{\text{SiIV}} \) and log \( N_{\text{OVI}} \) values, which were typically not considered in previous modelings (e.g., SW09). For these limits, we only calculated the \( \chi^2 \) value when it is opposite to the limits, i.e., they are higher than the upper limit and lower than the lower limit; otherwise, the \( \chi^2 \) value is fixed to 1 for these limits. The uncertainties of the sight lines are one-sided, which we set according to the intrinsic scatters (i.e., the patchiness parameter to be derived later; Table 1). Therefore, the uncertainty of the limits in the stellar sample is set to 0.3 dex, while the AGN sample is set to 0.1 dex.

Previous studies show that the intrinsic column density scatters of the disk and the CGM are the major contributors of the deviation in the fitting (e.g., Bowen et al. 2008; SW09; Zheng19). The intrinsic scatter is modeled as the patchiness parameter \( (\sigma_p) \), which is an additional uncertainty attached to the measurement uncertainty as \( \sigma^2 = \sigma^2_\text{p} + \sigma^2_\text{m} \). \( \sigma_\text{p} \) is the final adopted uncertainty in the model fittings, and \( \sigma_\text{m} \) is the measurement uncertainty. There are two methods to implement the patchiness parameters. The first method varies the patchiness parameter to obtain the reduced \( \chi^2 = 1 \), which is adopted in SW09 (and references herein). The second method implements the patchiness uncertainty into the Bayesian model as introduced in Zheng19. These two methods obtain similar results, and we adopt the first method in our analyses. The calculated \( \sigma_p \) values are shown in Table 1, which leads to a reduced \( \chi^2 \) of 0.95–1.05, due to the significant figures. In SW09, the patchiness parameters of Si IV and O VI are 0.266 and 0.233, respectively. The larger patchiness parameters (0.30 and 0.23) in Table 1 are mainly due to the inclusion of upper or lower limits in our fittings and the exclusion of AGN sight lines, which normally have smaller scatters. For the AGN samples, the previous \( \sigma_p \) were 0.18 and 0.25 for Si IV and O VI, respectively (Savage03; Zheng19), which are larger than our values in Table 1 (0.13 and 0.15). The reduction of the patchiness parameter indicates that the radial distribution of the disk affects the AGN sample more significantly.

The fitting results are summarized in Table 2. Overall, the exponential function leads to smaller scale lengths or scale heights than the Gaussian function, because the exponential function has a slower decay with the same characteristic length. With the isotropic CGM, the \( R_GZ_E \) model (indicating the Gaussian function for the radial profile and exponential function for the vertical profile) is preferred with a significance of \( \Delta \chi^2 \approx 4 \) (inferred from the difference of the total \( \chi^2 \)).

Similarly, the anisotropic CGM models show that no specific model is preferred, which will be described and discussed in detail in Section 3.3. Therefore, we suggest that the current stellar and AGN samples cannot distinguish between the density profiles (exponential or Gaussian) of the warm gas disk, and we set the \( R_GZ_E \) model as the fiducial model.

All of our four models show that both the disk and the CGM components contribute significantly to the observed column densities in the AGN sight lines. Using \( n_{\text{HI}} \) as the characteristic column density of the disk, the disk component is comparable to the CGM component for both Si IV and O VI (Table 2). Previously, the plane-parallel slab model shows that the disk component has Si IV column density ranging from log \( N = \log n_{\text{HI}} = 13.36 \) to 13.56, and O VI from log \( N = 14.12 \) to 14.28 (SW09). These values are all larger than our values of 13.21–13.26 (Si IV) and 13.95–14.08 (O VI). The lower values of our disk component are because we take into account the contribution of the MW CGM to the ion column density measurements toward the AGN sight lines, whereas the plane-parallel slab model assumes no contribution from the CGM. Our fitting results show that the CGM components are 13.12–13.17 (Si IV) and 13.91–14.02 (O VI). These values are comparable with the Si IV and O VI column densities measured from transverse AGN sight lines at \( R \approx 100 \) kpc (\( \approx 0.5 R_{\text{vir}} \)) for low-redshift \( L^* \) galaxies (\( z \approx 0.5 \); Werk et al. 2013; Savage et al. 2014; Johnson et al. 2015). Although the sight lines through the MW CGM have a different geometry from the sight lines for external galaxies, this consistency indicates a decreasing column density dependence on the radius of a power law with a slope of about \( -1 \) (Werk et al. 2013).

For the disk component, although we cannot distinguish between the exponential and Gaussian profiles, the scale height \( (z_0) \) and the scale length \( (r_0) \) can be determined. In the fiducial model (\( R_GZ_E \)), the scale heights are 2.6 ± 0.6 kpc and 2.4 ± 0.6 kpc for Si IV and O VI, respectively. The scale lengths are 4.2 ± 1.2 kpc and 5.6 ± 1.7 kpc for Si IV and O VI, respectively. The scale lengths are first measured in this work for the MW warm gas disk.

The radial profile of the disk component is important to solve the divergence between the plane-parallel slab model (SW09) and the two-component disk–CGM model (Zheng19), which have different relative contributions between the disk and CGM components. In Figure 1, we predict the projected column density distribution (log \( N \sin[\theta] \)) as a function of \( |z| \)-height and Galactic latitude \( (b) \) using the \( R_GZ_E \) model with isotropic CGM with the best-fit parameters in Table 2.

Before introducing the plots, we define the observed scale height, which is an observable for the warm gas analysis. This parameter is defined as \( N \sin[b] / n_\odot \), where \( N \sin[b] \) is the projected column density observed from the Sun and \( n_\odot \) is the midplane ion density around the Sun. The observed scale height could be estimated as the \( z \)-height of the turnover point in the projected column density function of the \( z \)-height. For example, in the left panel of Figure 1, the observed scale height is about \( |z_{\text{obs}}| \approx 0.03 \) kpc at \( b = 0^\circ \), while it is \( |z_{\text{obs}}| \approx 1 \) kpc at \( b = 5^\circ \). This is different from the scale height \( z_0 \) defined in Equation (2), which is a constant over the entire sky. The scale height \( z_0 \) could be calculated as \( n_{r,\text{mp}} / n_{r,\text{amp}} \), where \( n_{r,\text{amp}} \) and \( n_{r,\text{mp}} \) are the column density toward \( b = 90^\circ \) (the normal
direction of the disk) and the midplane density at any given radius of \( r \).

The difference between the scale height (\( z_0 \)) and the observed scale height (\( z_{\text{obs}} \)) is mainly due to the radial density distribution of the disk component. Using two AGN sight lines as an example, one sight line is toward \( b = 90^\circ \), while another sight line is toward the anti-Galactic center (anti-GC; \( l = 180^\circ \)) direction at any Galactic latitude. Considering the calculations of the scale height and the observed scale height, the midplane densities are the same, because both densities are around the Sun. However, the projected column densities of the disk component are different: the term \( N_{\text{m}, \text{nd}} \) is always larger than \( N_{\text{m}, \text{nd}} \) at different \( b \). This is a result of the disk radial distribution, because \( N_{\text{m}, \text{nd}} \) could be approximated as \( N_{\text{m}, \text{nd}} \exp(-(r - r_0)/r_0) \), where \( r \) is always larger than \( r_0 \) for anti-GC sight lines. Therefore, we expect that the observed scale height is always lower than the real scale height for anti-GC sight lines. Also, because a low \( b \) leads to a small tan \( b \) value, the low-latitude sight lines need a longer path length to reach the same height. Thus, the effect of the disk radial distribution is more significant for low-latitude sight lines, and lower projected column densities are expected for these sight lines (the left panel in Figure 1).

The sight lines toward the GC (\( l = 0^\circ \)) is more complex, because the disk radial distribution leads to higher density around the GC. However, the stellar sight lines are mainly at low latitudes \( |b| \lesssim 5^\circ \). In our fiducial \( R_E Z_E \) model, the scale heights of both Si IV and O VI are higher than 2 kpc. Using this scale height and a Galactic latitude of \( 5^\circ \), one expects a radius difference of \( z_0/\tan|b| > 20 \) kpc to reach the scale height of the disk. With this radius difference, the final effect on the observed scale height will be a competition between the high-density gas around the GC and the low-density gas at large radii. Our numerical calculation shows that it is possible to have larger observed scale heights around the GC direction (the left panel in Figure 1). Therefore, the sight lines around the GC direction have higher projected column densities than those toward the anti-GC directions, due to the high-density gas at the GC. Because the solar system is at \( r_0 = 8.5 \) kpc, this difference is most significant around \( |z| = 8.5 \tan|b| \) kpc, which is \( \approx 0.7 \) kpc for \( |b| = 5^\circ \).

In the middle panel of Figure 1, we show the predicted projected column density for the AGN samples using the fiducial \( R_E Z_E \) model. Our model predicts that the projected column density has a dependence on both Galactic latitude and Galactic longitude, while the previous models only have a dependence on Galactic latitude (SW09 and Zheng19; the right panel of Figure 1). The log \( N \) dependence on both \( l \) and \( b \) is due to the radial profile of the disk component, so it is similar to the case in the disk-only model (the left panel of Figure 1), but for higher Galactic latitudes (\( |b| \geq 30^\circ \)). The projected column densities are generally higher toward the GC direction than the anti-GC direction, and all the values converge at \( |b| = 90^\circ \). The anti-GC sight lines show a more significant dependence on the Galactic latitude \( |b| \) (decreasing rapidly), which is due to the radial profile in our model. The Zheng19 model also

### Table 2

| Model | \( \log n_0 \) (cm\(^{-3}\)) | \( r_0 \) (kpc) | \( z_0 \) (kpc) | \( \log N_{\text{CGM}} \) (cm\(^{-2}\)) | \( \log N_{\text{m, nd}} \) (cm\(^{-2}\)) | Reduced \( \chi^2 \) (dof) | \( \log n_{\text{disk}} \) (cm\(^{-3}\)) | \( \log n_{\text{m, nd}} \) (cm\(^{-3}\)) | \( \log M_{\text{disk}} \) (M\(_{\odot}\)) |
|-------|---------------------|-------|--------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| \( R_E Z_E \) | \(-7.82 \pm 0.24 \) | \( 4.3 \pm 1.2 \) | \( 2.5 \pm 0.6 \) | \( 13.18 \pm 0.12 \) | \( 1.232 \) (201) | \(-8.68 \) | \( 13.21 \) | \( 3.78 \) |
| \( R_E Z_E \) | \(-8.21 \pm 0.16 \) | \( 8.3 \pm 1.5 \) | \( 2.8 \pm 0.7 \) | \( 13.14 \pm 0.15 \) | \( 1.182 \) (201) | \(-8.67 \) | \( 13.26 \) | \( 3.70 \) |
| \( R_E Z_G \) | \(-7.74 \pm 0.23 \) | \( 3.7 \pm 0.9 \) | \( 3.3 \pm 0.6 \) | \( 13.16 \pm 0.11 \) | \( 1.267 \) (201) | \(-8.73 \) | \( 13.22 \) | \( 3.80 \) |
| \( R_E Z_G \) | \(-8.21 \pm 0.15 \) | \( 7.4 \pm 1.1 \) | \( 3.5 \pm 0.7 \) | \( 13.12 \pm 0.14 \) | \( 1.202 \) (201) | \(-8.78 \) | \( 13.26 \) | \( 3.66 \) |

**Note.** Column 1: the model name; R and Z denote radial and vertical directions; E and G denote exponential and Gaussian profiles. Column 2: the density at the GC. Column 3: the scale length. Column 4: the scale height. Column 5: the CGM column density along the disk midplane ("mp"). For the isotropic CGM model, this value is the same as the CGM column density perpendicular to the disk. Column 6: the CGM column density perpendicular to the disk ("nd" denotes the normal line). Column 7: the reduced \( \chi^2 \) and the degree of freedom. Column 8: the ion density at the solar system. Column 9: the disk column density toward \( b = 90^\circ \) at the solar system. Column 10: the disk mass of ions.
reproduces this feature, but in a different way. The Galactic latitude dependence in the Zheng19 model is due to the term of $N_{\text{CGM}} \sin b$. The model does not have a dependence on the Galactic longitude, so it does not reproduce the feature of GC sight lines having a higher column density than anti-GC sight lines (also see Figure 5 in Zheng19 and Figure 7 in Wakker et al. 2012).

### 3.3. The Anisotropy of the CGM Component

In the previous section, we adopted the isotropic CGM assumption from Zheng19. However, this isotropic CGM profile over the entire sky may not best represent the gas density distribution in the CGM. For example, Bordoloi et al. (2011) found that the absorption features are stronger along the minor axis using Mg II absorption lines for external galaxies (also see Lan & Mo 2018). Aside from the absorption strength, Martin et al. (2019) found that the nondetections of Mg II are mainly along the minor axis (perpendicular to the disk), which indicates a lower detection rate along the minor axis. Therefore, we consider the azimuthal variation of the CGM in our 2D disk–CGM model of the MW.

For the MW, the azimuthal variation of external galaxies is equivalent to a variation of the CGM column densities as a function of Galactic latitude. We refine our 2D disk–CGM model by changing the CGM density from an isotropic distribution to an anisotropic distribution with a dependence on Galactic latitude. In this model, we define two characteristic CGM column densities: the column density along the disk ($N_{\text{mp}}$; denoting the midplane) and the column density perpendicular to the disk ($N_{\text{nd}}$; denoting the normal direction of the disk). These two directions are similar to the major and minor axis directions for external galaxies. For simplicity, we assume that the CGM column density depends on the Galactic latitude $b$ as an elliptical function:

$$\log N_{\text{CGM}}(b) = \log^2 N_{\text{mp}} \cos^2 b + \log^2 N_{\text{nd}} \sin^2 b,$$

where $N_{\text{mp}}$ and $N_{\text{nd}}$ are free parameters in our model. For AGN sight lines, the term $N_{\text{CGM}}$ in Equation (2) has a dependence on the Galactic latitude ($N_{\text{CGM}}(b)$). In this model, we assume the variation of the CGM column density is in the logarithmic scale rather than in the linear scale, i.e., $N_{\text{CGM}}(b) = (N_{\text{mp}}^2 \cos^2 b + N_{\text{nd}}^2 \sin^2 b)^{1/2}$. In the linear scale variation model, if $N_{\text{nd}}$ is much larger than $N_{\text{mp}}$ (e.g., by a factor of $>3$), the CGM column density will be dominated by $N_{\text{nd}} \sin b$, and $N_{\text{mp}}$ cannot affect the fitting results. Therefore, the linear scale variation model does not have the ability to trace the large-amplitude CGM variation (i.e., $|\log N_{\text{nd}} - \log N_{\text{mp}}| > 0.5$ dex).

The $\chi^2$-fitting results show that the anisotropic CGM model is significantly better than the isotropic CGM model (Table 2). The total $\chi^2$ values are reduced by 15.6–26.4 and 15.7–21.2 for Si IV and O VI, respectively. The mean values of the $\chi^2$ difference are 20.8 and 18.5, which lead to a $4.6\sigma$ and $4.3\sigma$ significance considering that the degree of freedom (dof) is reduced by 1. According to the fitting, the CGM column density is higher along the normal direction of the MW disk ($N_{\text{nd}}$) than in the direction along the disk ($N_{\text{mp}}$) by 0.6–0.9 dex and $\approx 1.0$ dex for Si IV and O VI, respectively. The differences between $N_{\text{nd}}$ and $N_{\text{mp}}$ are consistent for different disk density profiles (exponential or Gaussian). This consistency indicates that the CGM anisotropy is a real feature rather than an artificial feature due to the choice of disk density profiles. Therefore, we suggest that the anisotropic model is preferred at least at a level of $4.0\sigma$ for both Si IV and O VI distributions. Combining these two ions together, the significance is about 6.5$\sigma$. However, this result does not imply that the CGM has an elliptical geometry, and it is even unknown whether this feature is completely due to the CGM, which will be discussed in Section 4.3.

Adopting the anisotropic CGM model does not affect the disk parameters significantly, but one interesting difference is the larger scale length. This is the result of the smaller CGM column density at low Galactic latitudes. In the isotropic CGM model, the CGM column density is dominated by the AGN sample at high Galactic latitudes. This isotropic column density ($\approx N_{\text{nd}}$) is higher than the real column density at low Galactic latitudes ($N_{\text{mp}}$) and suppresses the extension of the disk component along the radial direction. In the fiducial $R_z\Sigma_z$ disk model with an anisotropic CGM, the scale lengths are $5.3 \pm 1.4$ kpc and $7.8 \pm 2.4$ for Si IV and O VI, respectively. These numbers indicate that the warm gas disk is more extensive than the stellar disk ($\approx 2$ kpc; Bovy & Rix 2013) and the H1 disk ($\approx 3.5$ kpc; Kalberla & Dedes 2008) at about 2$\sigma$.

Column density predictions by the preferred models ($R_z\Sigma_z$ disk with anisotropic CGM) are compared to the observations in Figures 2 and 3 for Si IV and O VI, respectively. We plot the
stellar samples in the top panels, which generally follow the model (REZE disk with isotropic CGM; Figure 1) described in Section 3.2. Different from the plane-parallel slab model (SW09), we predict that the maximum projected column density has a dependence on Galactic latitude due to the radial profile of the disk (Section 3.2). However, the difference

Figure 2. The comparison between the 2D disk–CGM model predictions and observations for Si IV. Top panels: the comparison for the stellar sample. Two plots are color-coded in Galactic latitude ($b$; left) and Galactic longitude ($l$; right), respectively. Lower $|b|$ sight lines have lower projected column densities because these sight lines are more affected by the disk radial distribution (i.e., they need longer path lengths to reach the same height). Sight lines toward the GC have higher projected column densities due to the high ion density around the GC. Middle panels: the global variation of the total column densities for the AGN sample plotted in the Aitoff projection (the left panel). In the left panel, the white diamond-like region at the GC ($l = 0^\circ$ and $b = 0^\circ$) has column densities of $\log N > 14.2$, so it is left as a blank region. The model predicts that the minimum column density for AGN sight lines occurs around Galactic latitudes of $30^\circ–50^\circ$, which is a result of the competition between the disk component (the minimum at $b = 90^\circ$) and the CGM component (the minimum at $b = 0^\circ$). The right panel is the residual of $\log N(\text{Observation}) - \log N(\text{Model})$, which mainly shows the NS asymmetry (discussed in Section 4.4). Lower panels: the comparison between the anisotropic CGM model (left panel) and the isotropic CGM model (right panel). The anisotropic CGM model is 4.6σ better than the isotropic CGM model by reducing the total $\chi^2$ by a value of 20.8. The anisotropic CGM model reproduces the sharp decrease of the projected column density at low Galactic latitudes better for sight lines toward the anti-GC ($|l| = 180^\circ$; also see Figure 3).
between low and high Galactic latitude sight lines does not show up for the observed scale heights, because there are no high-\(|z|\) stellar sight lines at low latitude \((b \lesssim 3^\circ)\), which are expected to follow the purple lines in the top-left panels. The observations show the longitude dependence of the projected column density, because the sight lines toward the anti-GC generally have lower projected column densities than the sight lines toward the GC.

The middle panels show the global variation of the total column densities predicted for AGN sight lines. It is of interest to find that the predicted global minimum among the AGN sight lines occurs around \(|b| = 30^\circ-50^\circ\) around the anti-GC, which is the combination of the disk variation and the anisotropic CGM. The disk component has a minimum column density, due to the shortest path length, around the polar regions \((|b| \approx 90^\circ)\), while the anisotropic CGM component in

**Figure 3.** The comparison between model predictions and observations for O VI. Each panel is the same as in Figure 2. For the top panels, we also plot the Bowen et al. (2008) sample, which is not included in the fitting. For O VI, the anisotropic CGM model is 4.3\(\sigma\) better by reducing the total \(\chi^2\) by a value of 18.5.
our model has the minimum along the disk radial direction ($|b| = 0^\circ$). Then, considering these two effects together, the minimum of the total column density will be around $|b| \approx 45^\circ$. Observationally, this feature was found by Wakker et al. (2012), showing an O VI deficit region at $l = 70^\circ$–280$^\circ$, $b = -60^\circ$ to $-10^\circ$. This deficit is clearer in the southern hemisphere, because the southern hemisphere has systematically lower column densities.

The projected column density of the AGN samples is plotted in the lower panels of Figures 2 and 3. The northern hemisphere sight lines have systematically higher column densities than those of the southern hemisphere by 0.1–0.2 dex. The origin of this NS asymmetry is beyond the scope of this paper, but we discuss it phenomenologically in Section 4.4. Here, we do not consider this NS column density asymmetry in our modeling. The predicted tendency stated in Section 3.2 matches the observations, which show that the anti-GC sight lines have lower projected column densities.

We find that the anisotropic model can better reproduce the large log $N$ variation at lower Galactic latitudes for two reasons (Figures 2 and 3). First, the variation of the projected column density at low latitudes is mainly caused by the radial variation of the disk. The low column density along the disk radial direction (log $N$) allows a more extended disk, which increases the column density variation at low Galactic latitudes, because this variation is due to the variation of the disk (the middle panel of Figure 1). Second, the variation of the CGM column density leads to a steeper decrease of the projected column density at low latitudes around the anti-GC. Because the CGM column density is higher at $b = 90^\circ$, the total column density is also increased at high latitudes.

In all, we prefer the $R_2Z_k$ model with anisotropic CGM profile to other models (Figure 4). We examine the Si IV column density residuals to evaluate the performance of the plane-parallel slab model (SW09; left column), the two-component disk–CGM model (Zheng19; middle column), and our preferred model (right column). The plane-parallel slab model (SW09) fits the stellar sample well, which does not have unaccounted features in the residual (i.e., flat residuals over Galactic longitude), although there is a large scatter. However, there are significant unaccounted residuals in the residuals for the AGN sample (low residuals at low Galactic latitudes), although the intrinsic scatter is less than the stellar sample. The two-component disk–CGM model (Zheng19) has comparable residuals to our 2D disk–CGM model for the AGN sample, but the residuals show a peak around $l = 0^\circ$. Also, this model predicts a disk component of log $N = 12.1$, which is about one order of magnitude lower than that of SW09 and this work (log $N \approx 13.3$). The two-component disk–CGM model does not have distance constraints, so the log $N$ measurement from stellar sight lines cannot be reproduced in this model (Zheng19). Our new model could reproduce the column density measurements from both the stellar and the AGN sight lines equally well without unaccounted features in the residuals.

4. Discussion

4.1. The Comparison with Zheng19

Using archival data (Savage03; SW09; Zheng19), we build a 2D disk–CGM model to fit the Si IV and O VI column density measurements for warm gas moving at $|v| \lesssim 100\,\text{km} \,\text{s}^{-1}$ from both the AGN and stellar sight lines simultaneously. Previously, the plane-parallel slab model was commonly used to study the MW disk (Jenkins 1978; Bowen et al. 2008; SW09). However, the plane-parallel slab model cannot explain a mismatch between the AGN and stellar sample as noted and discussed in Zheng19, which is due to the lack of a CGM component in the plane-parallel slab model. Zheng19 introduced an additional isotropic CGM component to the plane-parallel slab model to account for the CGM contribution in the AGN sight lines. Here, we mainly compare our 2D disk–CGM model with the two-component disk–CGM model with a 1D disk (Zheng19).

For the model setting, the major difference is the inclusion of the disk radial distribution in our 2D disk–CGM model...
(Section 3.2), while a minor difference is an improvement from the isotropic CGM model to the Galactic latitude-dependent CGM model (Section 3.3). In Zheng19, the disk component is still the 1D plane-parallel slab model, which leads to a lower disk component. This is because the plane-parallel slab model has a constant projected column density of AGN over different Galactic latitudes. Therefore, the low Galactic latitude sight lines with low projected column densities (Figure 2 and Figure 3) lead to a low value of the disk component in the two-component disk--CGM model (Zheng19). For the CGM component, we find that the column density distribution of the MW CGM is likely to be a function of Galactic latitude instead of an isotropic one (Section 3.3). Because the AGN samples are mostly around the high latitude ($|b| \gtrsim 30^\circ$), this CGM modification leads to a significant difference ($\approx 0.7$–1.0 dex) for both Si IV and O VI at low Galactic latitudes between our models and the two-component disk--CGM model (Zheng19).

Another difference is the adopted statistical method, where we used the $\chi^2$ optimization, while Zheng19 used the Bayesian frame. Assuming a Gaussian distribution for the measurement uncertainty and the uniform prior, these two methods are equivalent in the sense of obtaining the minimum of the $\chi^2$ or the maximum of the likelihood. Aside from the method to obtain the fitting results, another difference in the statistical method is the choice of the likelihood or the uncertainty distribution. Zheng19 assumed the column density uncertainty follows a normal distribution (the linear scale) rather than a log-normal distribution, while the latter distribution is adopted in our models. Although the real distribution of the uncertainty is unknown, the log-normal distribution is more often used for data with a large variation (e.g., one order of magnitude). It is worth noting that these two distributions are similar to each other when the uncertainty is small ($\approx 0.02$ for most sight lines in Zheng19).

Zheng19 also used block bootstrapping to account for the possible unknown large-scale structures. From the residual map in Figures 2 and 3, we noticed the NS asymmetry, which is the most prominent variation over the entire sky. This feature is addressed and discussed phenomenologically in Section 4.4. In Section 4.5, we introduce several blocking tests for large-scale structures, which show consistent results with the unblocked fitting.

Another minor difference is that we obtain the patchiness parameter by reducing the reduced $\chi^2$ to 1, while Zheng19 implemented the patchiness parameter in the Bayesian frame. Again, Zheng19 assumed a normal distribution rather than a log-normal distribution for this intrinsic scatter. Therefore, their patchiness parameter estimate is $N_p = 1.4 \times 10^{14}$ in the linear scale. We convert it into the logarithmic scale by $\log_{10} e \times N_p \approx 0.179$, where $N_{p,IV}$ is the mean column density of the AGN sample of Si IV. This value is larger than the one in our models (0.13 dex; Table 1), and we suggest that this difference is mainly due to the inclusion of the disk radial profile to better account for the column density scatters as seen in the AGN data.

4.2. The Warm Gas Disk

The warm gas at $(1–5) \times 10^5$ K is important for gas assembly and recycling in a galaxy due to their high cooling rates and short lifetimes ($\approx 10$ Myr; Oppenheimer & Schaye 2013). Theoretically, this gas normally traces the interaction layer between cool and hot gases, and the cooling from hotter mediums (Gnat et al. 2010; Kwak et al. 2015). These phenomena are usually associated with galactic outflows (feedback processes), infall gas (gas accretion), and interactions between the disk and the CGM (McQuinn & Werk 2018; Qu & Bregman 2018). Therefore, one could obtain unique insights into the disk and the CGM formation by observing the warm gas.

The scale height is a key property of the warm gas disk, because it indicates how extensive the disk is, which is a test for the ionization mechanism and the gas origin (Bowen et al. 2008; SW09; Wakker et al. 2012). For example, the scale height should be larger for ions with higher ionization potentials under collisional ionization equilibrium (CIE). However, as shown in SW09, the O VI disk ($z_0 = 2.6 \pm 0.5$ kpc) has a slightly lower scale height than both Si IV ($3.2^{+1.0}_{-0.6}$ kpc) and C IV ($3.6^{+1.0}_{-0.8}$ kpc) in the SW09 model. This phenomenon might indicate that the Galactic Si IV and O VI are produced under different ionization mechanisms (SW09).

However, as stated in Section 3.2, we find that the Si IV scale height is reduced from $3.2^{+1.0}_{-0.6}$ kpc (SW09) to $2.6 \pm 0.6$ kpc (the $R_g Z_g$ model with the anisotropic CGM). The O VI scale height ($2.6 \pm 0.6$ kpc) is similar to that of SW09 ($2.6 \pm 0.5$ kpc). Therefore, our models do not support Si IV and O VI having different scale heights. The different behaviors between the Si IV and O VI scale heights are because of the inclusion of the disk radial profile and the anisotropic CGM component, the different samples, and the exclusion of AGN sight lines around the north Galactic polar region in SW09.

Aside from the scale heights, we find that the scale lengths are also similar between Si IV and O VI within 1$\sigma$. Therefore, we consider whether both of these ions follow the same density profile distributions as the disk component. A joint fitting model is applied to the Si IV and O VI samples simultaneously, where we tie the parameters of the O VI model to the Si IV model, including the scale length ($r_0$), the scale height ($z_0$), and the CGM difference between two axes ($\Delta \log N(CGM)$). In the model where the three parameters are all tied (Table 3), the difference in the total $\chi^2$ is 3.51 compared to the best model with all parameters free (the models in Table 2). Because the best model has three more dof, it is $1\sigma$ better than the most limited model, so the best model is not a significantly better model. We also tie these three parameters in turn to check which is the most dominant factor in the $\chi^2$ difference. We find that tying the scale length leads to the highest $\chi^2$, but the difference is still insignificant. Therefore, we prefer the most limited model with all three parameters tied and suggest that there is no significant difference in the density profile between Si IV and O VI adopting the new models.

Our model measures the scale length of the warm gas disk of the MW for the first time. We can further estimate the total mass of the warm gas disk of the MW. First, we obtain the total number of ions ($N_{\text{disk}}$) for Si IV or O VI within the warm gas disk by integrating the ion number density over the radial and vertical directions:

$$N_{\text{total}} = n_0 \int_0^{R_{\text{ vir}}} dr \exp \left( -\frac{r}{r_0} \right) \int_{-R_{\text{ vir}}}^{R_{\text{ vir}}} dz \exp \left( -\frac{|z|}{z_0} \right).$$

Then, we calculate the masses of the Si IV- or O VI-bearing gases, we assume the warm gas has solar
metallicity and adopt log(Si/H) and log(O/H) solar abundance values from Asplund et al. (2009). Also, we assume the average ionization fraction of 0.2 and 0.1 for Si IV and O VI, respectively (about half of the maximum in CIE or photoionization equilibrium (PIE) to represent the average ionization fraction; Gnat & Sternberg 2007; Oppenheimer & Schaye 2013). Then, the expected total number of hydrogen atoms is \( N_{HI} = N_{disk}^{HI} \times f/a \), where \( f \) is the ionization fraction of Si IV or O VI, and \( a \) is the abundance of silicon or oxygen. Taking the helium mass into account, the total mass of the warm gas disk is \( 1.3 \times N_{HI} m_{H} \), where \( m_{H} \) is the hydrogen atom mass. Finally, the derived total masses of the warm gas disk based on Si IV and O VI are

\[
\log(M_{HI}/M_{⊙})_{Si\ IV} = (7.6 \pm 0.1) - \log f_{Si\ IV}^{0.2} - \log \frac{Z}{Z_{⊙}},
\]

\[
\log(M_{HI}/M_{⊙})_{O VI} = (7.6 \pm 0.2) - \log f_{O VI}^{0.1} - \log \frac{Z}{Z_{⊙}},
\]

which are similar to each other.

The similarities of the shapes and masses between the Si IV and O VI disks indicate that these two ions might trace the same gases. However, it does not mean that these two ions are coplanar, because the ion ratio (Si IV/O VI) shows large scatter (\( \approx 0.5 \) dex; SW09). Si IV and O VI occupy the same space at large scale (Galactic scale) due to the similarities of the disk shapes, but these two ion-bearing gases are too clumpy to be noncoplanar at small scale (single cloud size; kiloparsec size; Werk et al. 2019). The Si IV gas is clumpier than O VI because it has larger intrinsic scatters (the patchiness parameter; Table 1). The same shapes of the Si IV and the O VI disk profiles from our models indicate that the warm gas disk cannot be in equilibrium. If these ions are in photoionization equilibrium, the Si IV gas should have a larger scale height, while the thermal-supported collisional disk predicts the opposite behavior.

A possible explanation of the same scale heights for Si IV and O VI is that these ions are produced by feedback processes (e.g., the Galactic fountain; Bregman 1980; Melso et al. 2019). In the Galactic fountain, the gas could be IVCs, which are separate clouds (Wakker et al. 2008; Shull et al. 2009; Werk et al. 2019). Then, the Si IV gas is close to the core of H I, while the O VI gas is likely to be the envelope, because Si IV has a lower excitation potential. The scale heights of these two ions are both set by the ejection due to Galactic feedback. The Si IV gas is clumpier than the O VI gas, because as an envelope, the O VI gas should have a larger volume-filling factor.

As a comparison to the neutral gas, the H I disk has a total mass of \( 7.1 \times 10^{9} M_{⊙} \), a scale height of 0.15 kpc, and a scale length of 3.25 kpc within 30 kpc (Kalberla & Dedes 2008; Nakanishi & Sofue 2016). Aside from the thin H I disk component, there is also a more extensive H I disk with a scale height of 1.6 \( \pm 0.6 \) kpc, which contains a mass of \( 3.2 \times 10^{9} M_{⊙} \) (called the H I halo in Marasco & Fraternali 2011). The warm gaseous disk has a larger scale height than the thick H I disk, while the mass is about one order of magnitude lower.

### 4.3. The Anisotropic CGM

As stated in Section 3.2, the preferred CGM component in our model is anisotropic with a dependence on Galactic latitude. The joint fitting of Si IV and O VI shows that there is an enhancement of \( \Delta \log N = 0.82 \pm 0.32 \) for the column density perpendicular to the disk compared to the direction along the disk. It is worth noting that although the component is called “CGM,” it does not mean that this enhancement of the column density is completely due to the CGM of the MW. This column density enhancement could be due to the enriched CGM of the MW or the interaction layer between the disk and the CGM (e.g., the interface layers around low- to intermediate-velocity clouds).

In the first scenario, the CGM above the disk is enriched by feedback processes from the disk which ejected (and recycled) materials/metals into the CGM. Also, the escaping ionizing fluxes are much more intense in the z-direction, which could lead to higher ionization states (Si IV and O VI) by photoionization. Another possibility is that there is an interaction layer between the disk and the halo gas above the disk, such as the Galactic fountain (Bregman 1980), which can be observed as low- to intermediate-velocity clouds (Wakker et al. 2008; Werk et al. 2019). If this component cannot be included in the disk component in our modeling, then it has to be attributed to the anisotropic “CGM” component, which might be the case here. Although these two possibilities are both associated with the feedback processes, the difference is the location of the gases, which could affect the estimation of the mass of the MW warm CGM. However, current observations cannot determine the location of these gases. Hereafter, we assume it is the enriched CGM scenario.

| Ion  | log \( n_{HI} \) (cm\(^{-3}\)) | \( r_{0} \) kpc | \( z_{0} \) kpc | \( \Delta \log N^{CGM} \) dex (cm\(^{-2}\)) | log \( N_{HI}^{CGM} \) (cm\(^{-2}\)) | Reduced \( \chi^{2} \) (dof) | log \( n_{disk}^{HI} \) (cm\(^{-3}\)) | log \( n_{disk}^{O VI} \) (cm\(^{-3}\)) | log \( M_{disk} \) (\( M_{⊙} \)) |
|------|------------------|-----------|---------|-----------------|-----------------|----------------|-----------------|-----------------|-----------------|
| Si IV | \(-8.02 \pm 0.12\) | \(6.1 \pm 1.2\) | \(2.6 \pm 0.4\) | \(0.82 \pm 0.32\) | \(13.32 \pm 0.07\) | 1.126 (376) | \(-8.63\) | 13.28 | 3.91 |
| O VI  | \(-7.22 \pm 0.12\) | ...       | ...     | ...             | ...             | ...             | ...             | ...             | ...             |
| Si IV | \(-8.04 \pm 0.13\) | \(6.1 \pm 1.2\) | \(2.9 \pm 0.5\) | \(0.86 \pm 0.43\) | \(13.30 \pm 0.08\) | 1.121 (374) | \(-8.64\) | 13.30 | 3.93 |
| O VI  | \(-7.21 \pm 0.12\) | ...       | ...     | ...             | ...             | ...             | ...             | ...             | ...             |
| Si IV | \(-7.92 \pm 0.16\) | \(5.2 \pm 1.2\) | \(2.6 \pm 0.4\) | \(0.69 \pm 0.32\) | \(13.32 \pm 0.07\) | 1.117 (374) | \(-8.64\) | 13.26 | 3.86 |
| O VI  | \(-7.36 \pm 0.13\) | \(8.0 \pm 2.3\) | ...     | \(0.99 \pm 0.49\) | \(14.19 \pm 0.08\) | ...             | \(-7.82\) | 14.08 | 4.56 |
| Si IV | \(-7.96 \pm 0.16\) | \(5.5 \pm 1.2\) | \(2.7 \pm 0.5\) | \(0.81 \pm 0.32\) | \(13.32 \pm 0.08\) | 1.118 (374) | ...             | 13.29 | 3.89 |
| O VI  | \(-7.32 \pm 0.15\) | \(7.5 \pm 2.1\) | \(2.4 \pm 0.5\) | ...             | \(14.18 \pm 0.08\) | ...             | \(-7.82\) | 14.06 | 4.50 |

\( \Delta \log N^{CGM} = \log N_{HI}^{CGM} - \log N_{HI}^{CGM} \). Positive values indicate that the CGM column density is higher in the direction perpendicular to the disk log \( N_{HI}^{CGM} \) than in the radial direction (log \( N_{HI}^{CGM} \)).

Note. Every two lines are one model, because these are joint models for both Si IV and O VI. The blank parameters of O VI are tied to Si IV.
To estimate the mass of the warm CGM, we calculate the average CGM column density over the entire sky, which is \( \frac{1}{2} \int_{-\pi/2}^{\pi/2} \rho_{\text{CGM}}(b) \cos b \, db \). The average CGM column densities are \( \log N = 12.84 \) and \( \log N = 13.70 \) for Si IV and O VI, respectively. The maximum radius of the CGM is fixed as the virial radius of the MW (250 kpc). The total ion mass is \( \log(M/M_\odot) = (5.6 \pm 0.2) + 2 \log(R_{\text{max}}/250 \text{ kpc}) \), assuming a uniform density distribution for Si IV and \( \log(M/M_\odot) = (6.3 \pm 0.2) + 2 \log(R_{\text{max}}/250 \text{ kpc}) \) for O VI, where \( R_{\text{max}} \) is the maximum radius of the CGM. The metallicity of the MW CGM is assumed to be 0.5 \( Z_\odot \) (Bregman et al. 2018) and the average ionization fraction is about half of the peak from the CIE or PIE (similar to the disk calculation in Section 4.2). Then, the Si IV- and O VI-bearing gases have masses of

\[
\log(M/M_\odot)_{\text{Si IV}} = (9.8 \pm 0.2) - \log \frac{f_{\text{Si IV}}}{0.2} - \log \frac{Z}{0.5Z_\odot},
\]

\[
+ 2 \log \frac{R_{\text{max}}}{250 \text{ kpc}}
\]

\[
\log(M/M_\odot)_{\text{O VI}} = (9.8 \pm 0.2) - \log \frac{f_{\text{O VI}}}{0.1} - \log \frac{Z}{0.5Z_\odot},
\]

\[
+ 2 \log \frac{R_{\text{max}}}{250 \text{ kpc}}
\]

(6)

Different from the disk component, we cannot constrain whether Si IV and O VI have similar shapes for the CGM, but if we assume they follow the same density profile, the masses are the same for these two ions. If one wants to estimate the mass for the interaction-layer scenario, one could use \( \log N = 12.50 \) and \( \log N = 13.36 \) instead in the mass estimation, which is a difference of \( \approx 0.34 \) dex.

The mass of the CGM has a dependence on the radial profile of the density. Although the radial profile of the warm gas cannot be determined using current observations for the MW, we show the effect of this variation as follows. For simplicity, we assume a \( \beta \)-model of \( n(r) = n_0 r^{-3/\beta} \) (a power-law model), which is empirical for the MW hot gas (Li & Bregman 2017) and warm gas in external galaxies (Werk et al. 2013; Johnson et al. 2015). Then, the new CGM mass is

\[
M_\beta = \frac{1 - 3\beta}{1 - \beta} \frac{R_{\text{max}}^{3 - 3\beta} - R_{\text{min}}^{-3 + 3\beta}}{R_{\text{max}}^{3 - 3\beta} - R_{\text{min}}^{3 - 3\beta}},
\]

where \( M_\beta \) is the mass in the \( \beta \)-model, while \( M_\alpha \) is the mass in the uniform density model (Equation (5)). \( R_{\text{max}} \) and \( R_{\text{min}} \) are the maximum and the minimum radii. With a boundary of 10 kpc and 250 kpc, the \( M_\beta/M_\alpha \) ratio is 0.24 with \( \beta = 1/2 \) (the theoretical hydrostatic equilibrium solution; Mo et al. 2010), which is a correction of \( \approx 0.6 \) dex for Equation (6). Generally, a larger \( \beta \) leads to a smaller mass of the CGM. Varying \( \beta \) from 1/3 to 2/3, the mass ratio varies from 0.45 to 0.12, and the mass is always lower than the uniform model. Therefore, we suggest that the mass in Equation (6) is the upper limit if the radial profiles of Si IV and O VI are decreasing at larger radii with the same assumptions of the abundance and the ionization fraction. The suggested mass region is \( \log(M/M_\odot) \approx 8.9 - 9.5 \) with a correction of \( -\log(Z/0.5Z_\odot) \).

The mass of the HVCs was not included in the previous discussion, because the Savage03 and Zheng19 samples only measured absorption features at low and intermediate velocities (\( |v| \lesssim 100 \text{ km s}^{-1} \)). One of the major contributors of the HVCs is the Magellanic System (MS), which has a total mass of \( \log(M/M_\odot) \approx 9.3 \) for atomic and warm ionized gases: \( \approx 4.9 \times 10^8 M_\odot \) in H I, \( \approx 1.0 \times 10^8 M_\odot \) in the warm gas in MS, and \( \approx 5.5 \times 10^8 M_\odot \) in the envelope of the MS (Brüns et al. 2005; Fox et al. 2014). Aside from the MS, other HVCs have a total H I mass of \( 2.6 \times 10^7 M_\odot \) (Wakker 2004; Putman et al. 2012). Assuming other HVCs have a similar H I/total warm gas ratio to the MS (1:4), the total mass of the other HVCs is about \( 1 \times 10^7 M_\odot \) (Lehner et al. 2012). Then, the total HVC mass in the MW is \( \log(M/M_\odot) \approx 9.4 \), which is comparable to the derived mass of the low- and intermediate-velocity gas in this paper. Therefore, the total mass of the warm ionized gaseous halo is about \( \log(M/M_\odot) \approx 9.5-9.8 \) for the entire velocity range.

This derived mass is consistent with the mass of \( \log(M/M_\odot) \gtrsim 9.3 \) reported in Zheng19, who only used the Si IV AGN sample to estimate the CGM column density of the MW. Our estimation of the warm CGM mass is comparable to the Andromeda galaxy, which has a total mass of \( \log(M/M_\odot) \approx 9.1 - \log(Z/Z_\odot) \) for the warm gas (up to C IV; Lehner et al. 2015). The warm CGM mass of the MW is consistent with some \( L^* \) galaxy samples at redshifts of \( z \lesssim 0.2 \) with \( \log(M/M_\odot) \approx 9.5-10.4 \) (Stocke et al. 2013), while there are also samples showing significant differences of \( L^* \) galaxies at \( z \approx 0.2 \) (e.g., COS-Halos), which have masses of \( \log(M/M_\odot) \approx 10.8-11.0 \) (Werk et al. 2014; Prochaska et al. 2017). However, significantly different masses are derived with different models using the same COS-Halos data, such as \( \log(M/M_\odot) \approx 10.1 \) (Stern et al. 2016; Bregman et al. 2018). These uncertainties suggest that the mass estimation of the CGM is model-dependent, but the local \( L^* \) galaxies (i.e., the MW and the Andromeda) do not favor a warm CGM with a mass comparable to the stellar mass.

### 4.4. Comments on the North–South Asymmetry

As shown in Figures 2 and 3, there is a significant NS asymmetry for the observed scale height of the AGN samples, which indicates the asymmetry of the warm gas distribution. This asymmetry is similar to the NS asymmetry of the Galactic X-ray background, which shows more soft X-ray emission in the northern hemisphere (Snowden et al. 1997). The physical origin of this asymmetry is unclear and beyond the scope of this paper. However, it is of interest to determine the origin of the warm gas asymmetry phenomenologically (i.e., the disk or the CGM).

Based on previous results, we assume Si IV and O VI have the same behaviors for both the disk and the CGM: the scale length, the scale height, and the CGM difference between two axes. Considering the NS asymmetry, there are three possible variations between the two hemispheres: the scale height of the disk, the disk normalization density, and the CGM column density. Here, we ignore the possible difference of the scale length, which is fixed to the same for both hemispheres. Then, this model can have different scale heights and different disk density normalizations between the north and south disks, and different azimuthal CGM column densities (Table 4). The total \( \chi^2 \) difference is 35.1, which is 5.3 times the difference of 3. The fitting reveals that the differences of the disk density normalizations and the CGM column density normalizations
are close to zero, within the uncertainty. The largest variation is due to the difference in the scale heights.

Quantitatively, we vary these parameters individually to determine the dominant factor (Table 4). The fitting results show that the scale height is the dominant parameter rather than the disk normalization or the CGM normalization with the smallest reduced $\chi^2$. Varying only the scale height, this model is $0.8\sigma$ worse compared to the “best” model (with all parameters free) by $\Delta \chi^2 = 1.78$ and the dof difference of 2. Similarly, the disk normalization model is $1.5\sigma$ away from the “best” model. Although the scale height model is preferred, it is not a large statistical difference between these two models with varied disk shapes. Compared to models where the disk is varied, the model with CGM-only differences is less preferred because it is $2.9\sigma$ away from the “best” model.

In the different scale height models, the northern and the southern hemispheres have scale heights of $3.5 \pm 0.5$ kpc and $2.3 \pm 0.4$ kpc, respectively. The difference in the scale heights is about $1.2$ kpc, which is at about $2\sigma$. As shown in Figure 5, a larger scale height leads to a larger scatter at low latitudes, which is favored by the observations. In this model, the variation of the model parameters does not affect the mass estimation in Sections 4.2 and 4.3, which are all within $1\sigma$. Therefore, we do not report new values for the masses of both the disk and the CGM.

### 4.5. The Possible Nonuniform Structures

It is well known that the warm gas disk and CGM of the MW both have lots of structures, e.g., the Fermi Bubbles (FBs), HVCs, and the Local Bubble. These structures may have a nonuniform contribution to the measured column density of warm gases, which is opposite to our assumption that the density profile of the warm gas can be modeled by smooth functions. Therefore, we adopt the blocking method to test whether these possible nonuniform structures affect our fittings; a similar method has also been used by Zheng19 to study the underlying gaseous structures in the MW halo. For the blocking, we mean to block some part of the sky to obtain a new set of sample and fitting results. The (non-)consistency between the blocked and unblocked fitting results shows hints of the effect of the possible structures in the blocked region.

First, we consider a known structure—the FBs. Bordoloi et al. (2017) and Karim et al. (2018) showed the enhancement of the HVCs due to the FBs (both the northern and southern bubbles), which are not included in our modeling. Therefore, we block the sky region of $-60^\circ < b < 60^\circ$ and $-30^\circ < l < 30^\circ$ to avoid the AGN sight lines (17 for SiIV and five for OVI) through the FB. The stellar sight lines are not masked out because none of the stars are distant enough to be in the FB. The fitting results are $R_0 = 5.5 \pm 1.1$ kpc, $z_0 = 2.9 \pm 0.5$ kpc, and the CGM

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**Table 4**

| Ion    | $n_0^a$ (cm$^{-3}$) | $\Delta n_0^{NSN}$ (cm$^{-3}$) | $r_0$ kpc | $z_0^a$ kpc | $z_0^b$ kpc | $\Delta \log N_{CGM}$ (dex cm$^{-2}$) | $R_{CGM}^a$ (cm$^{-2}$) | $R_{CGM}^b$ (cm$^{-2}$) | Reduced $\chi^2$ (dof) |
|--------|---------------------|---------------------|-------|-----------|-----------|-----------------|-----------------|-----------------|---------------------|
| Si IV  | $-8.01 \pm 0.12$    | $0.06 \pm 0.05$     | $6.0 \pm 1.1$ | $3.4 \pm 0.6$ | $2.5 \pm 0.4$ | $0.92 \pm 0.46$    | $13.21 \pm 0.14$ | $-0.09 \pm 0.15$ | $1.034 (373)$      |
| O VI   | $-7.20 \pm 0.12$    |                     |       |           |           | $13.96 \pm 0.16$ |                  |                 |                     |
| Si IV  | $-7.97 \pm 0.12$    | $0.14 \pm 0.02$     | $6.0 \pm 1.0$ | $2.9 \pm 0.4$ | $0.98 \pm 0.46$ | $13.26 \pm 0.08$ |                  |                 | $1.045 (375)$      |
| O VI   | $-7.17 \pm 0.11$    |                     |       |           |           | $14.06 \pm 0.11$ |                  |                 |                     |
| Si IV  | $-8.03 \pm 0.12$    |                     | $5.9 \pm 1.1$ | $3.5 \pm 0.5$ | $2.3 \pm 0.4$ | $0.83 \pm 0.41$ | $13.26 \pm 0.08$ |                  | $1.039 (375)$      |
| O VI   | $-7.23 \pm 0.12$    |                     |       |           |           | $14.04 \pm 0.11$ |                  |                 |                     |
| Si IV  | $-7.95 \pm 0.13$    |                     | $5.2 \pm 1.0$ | $2.5 \pm 0.4$ | $0.56 \pm 0.20$ | $13.40 \pm 0.06$ | $0.29 \pm 0.09$ |                  | $1.063 (375)$      |
| O VI   | $-7.18 \pm 0.12$    |                     |       |           |           | $14.25 \pm 0.06$ |                  |                 |                     |

**Notes.** Every two lines are one model, because these are joint models for both Si IV and OVI. The blank parameters of OVI are tied to those of Si IV.

$^a$ The disk density and the CGM column density are for the northern hemisphere.

$^b$ For the difference between the two hemispheres, the positive value indicates that the northern hemisphere is higher than the southern hemisphere.
difference of 0.80 ± 0.34 dex. This solution is within 0.5σ from the fiducial model (Table 3). The mass estimates of the warm gas are all within uncertain of 0.2 dex for both the disk and the CGM. Therefore, we suggest that the FBs do not contribute to the low- to intermediate-velocity warm gas significantly, although detailed studies on the FBs show evidence for the enhancement of HVCs (Bordoloi et al. 2017; Karim et al. 2018).

Then, we consider possible unknown large-scale structures, such as the possible connection between HVCs and IVCs (Sembach et al. 2003). Zheng19 used block bootstrapping to study it, while we consider this in a simple way. Following Zheng19, the sky is divided into eight regions of 90° × 90° based on the latitude and the longitude. Each region is blocked out in turn, so we have eight new samples with about 2/8 of the sight lines of the fiducial sample. We applied the joint model to these new samples. The fittings of the blocked sample lead to the parameter region of $R_0$ ≈ 5.2 – 7.4 kpc, $z_0$ ≈ 2.2 – 3.0 kpc, and $\Delta \log N_{\text{CGM}}$ ≈ 0.63 – 1.23. These results are all within the uncertainty (1σ) of the fiducial model, which indicates that there are no significant contributions from the unknown structures, and our assumption of the smooth profiles roughly holds at large scale.

5. Summary

We develop a 2D disk-CGM model for the MW absorption-line samples of Si IV and O VI. The radial density profile of the disk is introduced to determine if it alleviates the tension between the stellar sample and the AGN sample, where a thick warm disk is supported by the stellar sample (SW09) but not by the two-component disk-CGM model of the AGN sample (Zheng19). More details can be found in Section 4.1 for the difference between the new model and previous studies (e.g., SW09; Zheng19). Adopting the new model, we obtain the scale heights and the scale lengths for the warm gas disk traced by Si IV and O VI, and estimate the masses in both the gaseous disk and the gaseous halo. Here, we summarize our results:

1. For the MW, the preferred warm gas distribution has a 2D disk component ($R_{2D}Z_\beta$) with exponential radial and vertical profiles ($n(r, z) = n_0 \exp(-|z|/z_0)\exp(-(r/r_0))$) and an anisotropic CGM component (depending on Galactic latitude). The joint fitting of Si IV and O VI shows that these two ions could be modeled by the same density profile, which has a scale length of $r_0 = 6.1 ± 1.2$ kpc and a scale height of $z_0 = 2.6 ± 0.4$ kpc. The same shape of Si IV and O VI might indicate that these two ions are physically associated with each other despite the significant difference in their ionization potentials. This scale length is larger than the HI disk ($\approx$3–4 kpc) and the stellar disk ($\approx$2 kpc). In SW09, O VI was found to have a lower scale height than Si IV, which was suggested as evidence for the different ionization mechanisms between Si IV and O VI. However, our fitting shows that there is no significant difference between the Si IV and the O VI scale heights, but this does not mean that these two ions are cospatial.

2. From our best-fit model (the $R_{2D}Z_\beta$ disk and anisotropic CGM), the total mass of the warm gas disk (log $T$ ≈ 5) is about $\log (M/M_\odot)_{\text{Si IV}} = (7.6 ± 0.2) - \log (Z/Z_\odot)$.

3. The CGM component in our model makes a contribution to the column density comparable to that of the warm gas disk. Our modeling indicates that it has a higher column density in the direction perpendicular to the disk than in the direction along the disk at >4σ levels for both Si IV and O VI. Combining these two ions, the difference is 0.82 ± 0.32 dex at about 6.3σ between the vertical and radial directions. However, some of this difference may be due to an interaction layer close to the disk, which we attribute to the CGM.

4. The mass of the low- to intermediate-velocity |v| ≲ 100 km s$^{-1}$ warm (log $T$ ≈ 5) gas in the CGM is estimated to be log $(M/M_\odot) ≈ 9.8 ± 0.2$ with a uniform density distribution and a metallicity of 0.5 Z$_\odot$. When we adopt a β model (power law; $n(r) = n_0 r^{-\beta}$) to approximate the density profile to 250 kpc, the total mass will be reduced to log $(M/M_\odot) ≈ 9.5$ (β = 1/3), log $(M/M_\odot) ≈ 9.2$ (β = 1/2), and log $(M/M_\odot) ≈ 8.9$ (β = 2/3). Then, the total mass of the warm CGM is estimated to be log $(M/M_\odot) = 9.5 – 9.8$ for the MW, combined with the HVC mass of log $(M/M_\odot) = 9.4$ for the MW.

5. The projected column density (log $N \sin |b|$) of the AGN indicates a significant NS asymmetry. Our models suggest that this asymmetry is more likely due to an asymmetric disk rather than an asymmetric CGM at about 2σ. For the asymmetric disk, the variation of the density or the scale height cannot be distinguished, but the model with varying scale heights shows a smaller reduced χ$^2$ (at ≈0.7σ). The northern and the southern hemispheres have scale heights of 3.5 ± 0.5 kpc and 2.3 ± 0.4 kpc, respectively.

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References

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Boettcher, E., Zweibel, E. G., Gallagher, J. S., III, & Benjamin, R. A. 2016, ApJ, 832, 118
Bordoloi, R., Fox, A. J., Lockman, F. J., et al. 2017, ApJ, 834, 191
Bordoloi, R., Lilly, S. J., Knobel, C., et al. 2011, ApJ, 743, 10
Borthakur, S., Heckman, T., Strickland, D., Wild, V., & Schiminovich, D. 2013, ApJ, 768, 18
Borthakur, S., Heckman, T., Tumlinson, J., et al. 2015, ApJ, 813, 46
Bovy, J., & Rix, H.-W. 2013, ApJ, 779, 115
Bowen, D. V., Jenkins, E. B., Tripp, T. M., et al. 2008, ApJS, 176, 59
Bregman, J. N. 1980, ApJ, 236, 577
Bregman, J. N., Anderson, M. E., Miller, M. J., et al. 2018, ApJ, 862, 3
Brüns, K., Kerp, J., Staveley-Smith, L., et al. 2005, A&A, 432, 45
Cen, R., & Ostriker, J. P. 2006, ApJ, 650, 560
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Fielding, D., Quataert, E., McCourt, M., & Thompson, T. A. 2017, MNRAS, 466, 3810
