Probing the Anisotropy of the Milky Way Gaseous Halo-II: Sightline toward Mrk 509

A. Gupta1,2, S. Mathur3,4, and Y. Krongold1

1 Department of Biological and Physical Sciences, Columbus State Community College, Columbus, OH 43215, USA; agupta1@cscc.edu
2 Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA
3 Center for Cosmology and Astro-Particle Physics, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA
4 Instituto de Astronomía, Universidad Nacional Autonoma de Mexico, Mexico City, Mexico

Received 2016 May 23; revised 2016 November 2; accepted 2016 November 14; published 2017 February 24

Abstract

Hot, million degree gas appears to pervade the Milky Way halo, containing a large fraction of the Galactic missing baryons. This circumbalgal medium (CGM) is probed effectively in X-rays, both in absorption and in emission. The CGM also appears to be anisotropic, so we have started a program to determine CGM properties along several sightlines by combining absorption and emission measurements. Here we present the emission measure close to the Mrk 509 sightline using new Suzaku and XMM-Newton observations. We also present new analysis and modeling of Chandra HETG spectra to constrain the absorption parameters. The emission measure in this sightline is high, EM = 0.0165 ± 0.0008 ± 0.0006 cm−6 pc, five times larger than the average. The observed O VII column density N(O VII) = 2.35 ± 0.4 × 1016 cm−2, however, is close to the average. We find that the temperature of the emitting and absorbing gas is the same: log(T(K)) = 6.33 ± 0.01 and log(T(K)) = 6.33 ± 0.16 respectively. We fit the observed column density and emission measure with a β-model density profile. The central density is constrained to be between n0 = 2.8–6.0 × 10−4 cm−3 and the core radius of the density profile has a lower limit of 40 kpc. This shows that the hot gas is mostly in the CGM of the galaxy, not in the Galactic disk. Our derived density profile is close to the Maller & Bullock profile for adiabatic gas in hydrostatic equilibrium with an NFW dark-matter potential well. Assuming this density profile, the minimum mass of the hot CGM is 3.2 × 1010 M⊙.

Key words: galaxies: halos – Galaxy: evolution – Galaxy: formation – large-scale structure of universe – X-rays: diffuse background

1. Introduction

We have known for decades that stellar and ISM components of galaxies, including our own Milky Way, account for only a small fraction of their baryons, compared to the amount expected in their halos from the universal baryon fraction Ωb/Ωm = 0.17 (Sommer-Larsen 2006; Bregman 2007; Anderson & Bregman 2010; Gupta et al. 2012; Miller & Bregman 2013; Miller et al. 2016). As interesting as the missing baryons problem, is the missing metals problem; nearby galaxies are also short of metals expected from the star formation history of the universe (Shapley et al. 2003). Perhaps a solution to both of these problems lies in the highly ionized warm-hot gas in the circumbalgal medium (CGM) of galaxies. Recent theoretical models suggest that the CGM of galaxies contains a large reservoir of warm-hot gas accounting for the majority of galactic baryons (Feldmann et al. 2012; Stinson et al. 2012; Fang et al. 2013; Ford et al. 2013; Roca-Fabrega et al. 2016) and according to Peeples et al. (2014), the CGM could account for 40% of metals produced by star-forming galaxies. The distribution, spatial extent, and mass of this warm-hot gas provide important constraints to models of galaxy formation and the accretion and feedback mechanisms.

Although theoretical models predict the existence of the warm-hot gas in the CGM, detecting and characterizing the diffuse CGM has been difficult. Because of our special vantage point, our own Milky Way provides a unique opportunity to probe the CGM of a spiral galaxy. The warm-hot CGM gas can be effectively probed by highly ionized metals; the dominant transitions from such ions lie in the soft X-ray band. In the literature, there are multiple reports on the detection of redshift zero absorption lines due to O VII and O VIII (Nicastro et al. 2002; Wang et al. 2005; Williams et al. 2005; Fang et al. 2006, 2015; Bregman 2007; Miller & Bregman 2013). However, it is difficult to measure the extent, density, and mass of this warm-hot gas because of the inherent difficulty in using absorption line studies alone. While the absorption line column density is a product of density and pathlength, the emission measure is a product of density square and pathlength, so a combination of absorption and emission studies are required to break the degeneracy and thus fully characterize the warm-hot CGM. Indeed various broadband X-ray observations have revealed an extensive diffuse soft (<1 keV) X-ray background (SXRB). Shadow observations show that there is a significant contribution from the Galactic halo to SXRB (Snowden et al. 2000; Galeazzi et al. 2007; Henley et al. 2007; Smith et al. 2007; Henley & Shelton 2008; Gupta et al. 2009).

In Gupta et al. (2012, hereafter Paper I), combining Chandra observations of O VII and O VIII absorption lines and XMM-Newton and Suzaku measurements of the Galactic halo emission measure, we found that there is a huge reservoir of ionized gas around the Milky Way, with a mass of over 60 billion solar masses and a radius of over 100 kpc. Thus there appears to be more baryonic mass in the warm-hot CGM than in the entire disk of the Galaxy and as much mass in metals as in all of the stars in the disk. In Paper I, we compared absorption and emission values averaged over the whole sky. However, shadow observations and other studies of soft X-ray diffuse background show that the emission measure of the Galactic halo varies by an order of magnitude in different sightlines (Gupta et al. 2009; Henley et al. 2010). Therefore, it is crucial to determine the emission measure of emitting gas near absorption sightlines to understand the differences in physical properties of the CGM across the sky.
In Gupta et al. (2014, hereafter Paper II), we compared absorption and emission along two sightlines: toward Mrk421 and PKS2155-304. In these two sightlines, the observed column densities are similar, but observed emission measures are different, so their densities and/or pathlengths must be different. Indeed, we found that toward Mrk421 and PKS2155-304 the densities are $1.6_{-0.8}^{+2.6} \times 10^{-4}$ cm$^{-3}$ and $3.6_{-1.8}^{+3.5} \times 10^{-4}$ cm$^{-3}$ and pathlengths are $33_{-27}^{+65}$ kpc and $105_{-82}^{+200}$ kpc respectively. While the errors on the derived parameters are large, this provides suggestive evidence that the warm-hot gas in the CGM of the Milky Way is not distributed uniformly.

Here we expand on our previous work and constrain the physical properties (temperature, pathlength, density, and mass) of the CGM in the sightline toward Mrk 509. In Sections 2 and 3, we present a detailed analysis of our XMM-Newton and Suzaku (PI: Gupta) new observations of a blank sky field near Mrk 509. We also present a detailed reanalysis of the Chandra High Energy Transmission Grating (HETG) 2012 observation of Mrk 509. Kaastra et al. (2014) have analyzed and modeled the intrinsic absorbers of Mrk 509. Here we focus on the redshift zero absorption lines.

In Section 5, we present results with a uniform density model as well as a $\beta$-model. The discussion is presented in Section 7.

2. Observation and Data Reduction

A blank X-ray sky field (Off-field2) adjacent to Mrk 509 was observed by XMM-Newton and Suzaku. The observation IDs, dates, pointing directions, and exposure times are summarized in Table 1. Figure 1 shows the ROSAT All Sky Survey (RASS; 0.1-2.4 keV) image in the vicinity of Mrk 509, along with the XMM-Newton and Suzaku pointing of Off-field2. Mrk 509 was observed with Chandra Low Energy Transmission Grating (LETG) and High Energy Transmission Grating (HETG) in December 2009 and September 2012 respectively. We presented our results on the $z = 0$ O VII and O VIII absorption lines from the LETG observation in Paper I. In the following, we report on the data reduction of XMM-Newton and Suzaku observations of Off-field2 and Chandra HETG observation of Mrk 509.

2.1. XMM-Newton Observations

Off-field2 was observed by XMM-Newton for 60 ks on November 2013. The observation was performed with the filter using the full-frame (FF) mode for all the EPIC (European Photon Imaging Camera) cameras. In this work, we used data from the EPIC-pn and EPIC-MOS detectors.

We reduced the data using the XMM-Newton Extended Source Analysis Software (XMM-ESAS; https://heasarc.gsfc.nasa.gov/docs/xmm/esas/cookbook/xmm-esas.html)

Table 1
Summary of Observations for Off-field2 and Mrk 509

| Experiment | Target     | OBSID     | Start Date | Exposure (ks) | $l$ (deg) | $b$ (deg) |
|------------|------------|-----------|------------|--------------|-----------|-----------|
| XMM-Newton | Off-field2 | 722310201 | 2013 Nov 19 | 63           | 37.4      | −30.6     |
| Suzaku     | Off-field2 | 509043010 | 2014 May 07 | 61           | 37.4      | −30.6     |
| Chandra    | Mrk 509   | 13864     | 2012 Sep 04 | 170          | 35.9      | −29.8     |
|            | Mrk 509   | 13865     | 2012 Sep 07 | 99           | 35.9      | −29.8     |

Figure 1. RASS 3/4 keV band X-ray map in the vicinity of Mrk 509 (black circle). The white square marks the nearby blank X-ray sky field (Off-field2).
The Astrophysical Journal, 836:243 (10pp), 2017 February 20

Extracted after removing the point sources. Red curves correspond (from the unexposed regions of the cameras) spectra. The QPB spectra were calculated from a database of calculate corresponding quiescent particle background matrix spectral extraction scripts also calculated the redistribution mos and 4.8 background/sr for the MOS2 and pn respectively. We used the XMM-ESAS scripts we run the XISs with ftool xisrmfgen and xissimarfgen to produce the RMFs and ARFs. For the ARF calculations, we assumed a uniform source of radius 20′ and used a detector mask that removed the bad pixel regions. We extracted the spectra of non-X-ray background from a database of the night Earth data with ftool xisxbgen.

2.3. Chandra Observations

Mrk 509 was observed by Chandra HETG in 2012 for a total of 280 ks (ObsID: 13864 and 13865). The HETG is comprised of two gratings: the medium energy gratings (MEG) and the high energy gratings (HEG), which disperse spectra into positive and negative spectral orders. Since we are interested in oxygen absorption lines, we used the data from MEG only and reduced it using the standard Chandra Interactive Analysis of Observations (CIAO) software (v4.6) and Chandra Calibration Database (CALDB, v4.6.3) and followed the standard Chandra data reduction threads.6 First, we run the mkgrmf CIAO script to create the first-order positive and negative MEG RMFs, needed for spectral analysis of grating observations. Furthermore, to increase the S/N, we co-added the negative and positive first-order spectra with add_grating_orders and built the ARFs using the fullgarf CIAO script.

3. Spectral Analysis: Emission

We used Xspec for spectral analysis of XMM-Newton and Suzaku data. We used the χ² statistics as a goodness-of-fit measure and all errors are given at the 1σ confidence level. The goal of our XMM-Newton and Suzaku observations of Off-field2 is to measure the contribution of galactic halo emission to the soft diffuse X-ray background (SDXB) near Mrk 509. SDXB spectra have three distinct components: (1) a foreground component consisting of solar wind charge exchange (SWCX) and the local bubble (LB); this is modeled as an unabsorbed plasma with thermal emission in collisional-ionization equilibrium (CIE); (2) a background component made of unresolved extragalactic sources; this is modeled with an absorbed power law; and (3) Galactic halo emission; this is modeled as an equilibrium thermal plasma component absorbed by the gas in the Galactic disk.

Both the Galactic halo and foreground components (SWCX + LB) have similar spectral shape, primarily X-ray lines from highly ionized metals, mostly O VII and O VIII. As a result, disentangling the two is very difficult. To minimize the SWCX contribution, which varies both in spectral composition and flux on scales of hours to days, we use proton flux filtering (Smith et al. 2007; Yoshino et al. 2009). We obtained the solar wind proton flux data from OMNIWeb.7 Figure 3 shows the solar wind proton flux during XMM-Newton and Suzaku

6 http://cxc.harvard.edu/ciao/threads/index.html
7 http://omniweb.gsfc.nasa.gov/
observations of Off-field2. During the Suzaku observation, solar wind proton flux is much higher than during the XMM-Newton observation. We investigated the effect of the higher proton flux during Suzaku observation by comparing surface brightness of O VII Kα and O VIII Kα lines in XMM-Newton and Suzaku spectra. As expected, O VII Kα line intensity is higher by about a factor of 1.5 during the Suzaku observation compared to the XMM-Newton observation (Table 2), implying that the Suzaku spectra have significant contamination from SWCX. Thus, for further analysis, we use only the XMM-Newton spectrum of Off-field2.

### 3.1. Spectral Modeling: Emission

We simultaneously fit the XMM-Newton MOS1 and MOS2 filtered diffuse background spectra with the three component model noted above. Even after the data cleaning described in Section 2.1, there may remain some residual soft proton contamination (https://heasarc.gsfc.nasa.gov/docs/xmm/esas/cookbook/xmm-esas.html). This is modeled as an additional power law that was not folded through the instrumental response. We also modeled the instrumental Al and Si fluorescence lines at 1.49 and 1.74 keV respectively, with two Gaussians.

We use the APEC model with plasma temperature of $T = 1.2 \times 10^6$ K (frozen) and emission measure (EM) of 0.0032 cm$^{-6}$ pc (frozen) for the foreground component (SWCX plus LB). We determined the normalization/EM of the foreground component using data from Snowden et al. (2000) catalog of XRB shadows as described in detail in Paper II. We find five shadows in the catalog closest to our sightline with average foreground R12 count rates of $337 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$ corresponding to EM of 0.0032 cm$^{-6}$ pc.

The contribution from unresolved extragalactic sources is modeled with an absorbed power law. The Galactic column density was fixed to $N_H = 4 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990), and power-law slope and normalization were left as free parameters in the spectral fit.

Finally, we determine the hotter Galactic halo contribution, modeled as an equilibrium thermal plasma component absorbed by the gas in the galactic disk (Figure 4). We measured the galactic halo temperature of $\log T(K) = 6.33 \pm 0.01$ and emission measure of $0.0165 \pm 0.0008 \pm 0.0006$ cm$^{-6}$ pc. The first error indicates the statistical error, and the second error indicates the estimated systematic error due to our assumed foreground spectra (for details see Paper II). The EM toward Mrk 509 is unusually high, about five times the sky average of 0.0030 $\pm$ 0.0006 cm$^{-6}$ pc. Henley et al. (2007) have reported such high Galactic halo EM toward a filament in the southern Galactic hemisphere.

#### XMM-Newton

XMM-Newton pn spectrum is consistent with the MOS model ($\chi^2_p = 1.2$), though there are some residuals at energies of 0.4–0.7 keV. This might be due to under- or over-estimation of the pn particle background as discussed at https://heasarc.gsfc.nasa.gov/docs/xmm/esas/cookbook/xmm-esas.html. Thus for further calculations we use only the MOS2 spectrum fit results (Henley et al. 2010 have also used only the MOS data for galactic halo emission measurements).

### 4. Spectral Analysis: Absorption

For the spectral analysis of absorption along the sightline to Mrk 509, we binned the Chandra MEG spectra to 0.01 Å and analyzed using the CIAO fitting package Sherpa.

Since we are interested in $z = 0$ highly ionized metal lines, we fit the continuum spectrum in the 15–23 Å range with a
power law, absorbed by the Galactic column density. Mrk 509 is known to have intrinsic absorption (Kaastra et al. 2014 and references there in), so we fit the intrinsic absorbers of Mrk 509 with multiple Gaussians.

After fitting the continuum and intrinsic features, the $z = 0$ O VII Kα, O VII Kβ, and O VIII Kα absorption lines are detected with more than 3σ significance (Figure 5). We fit these lines with narrow Gaussian features of line width 1 mÅ. The best-fit line parameters and errors (calculated using the projection command in Sherpa) are given in Table 3 and the spectrum is shown in Figure 5. The measured equivalent widths (EWs) are consistent within 1σ error of our previous measurements (Paper I) done with the Chandra LETG 2009 observation.

The O VII Kα absorption line is clearly saturated in the Mrk 509 data. The measured $\frac{EW(Kβ)}{EW(Kα)}$ ratio is 0.56, much higher than the expected ratio of 0.156 for optically thin O VII lines. For the saturated lines like we observe here, converting the observed EWs to column densities is non-trivial. We used the method described in detail at Paper I to obtain constraints on the O VII column density: $\log N_{O VII} (\text{cm}^{-2}) = 16.6 \pm 0.4$ and the velocity dispersion parameter $b = 70–200 \text{ km s}^{-1}$. The measurement uncertainties are large due to the weak O VII Kβ line, but we can do better by using the code PHASE, as discussed below.

### 4.1. Fitting with PHASE

Our hybrid photo- and collisional-ionization code PHASE (Krongold et al. 2003) automatically takes into account line saturation by using Voigt profiles to fit absorption lines. The additional advantage of using the code is that it fits the entire 11.0 to 23 Å spectrum, taking into account lines that are not individually detected, providing better constraints. The fit provides constraints on the column density, velocity dispersion parameter and temperature of the absorbing plasma. Best-fit PHASE parameters are reported in Table 4 and the spectrum is shown in Figure 6. The O VII column density was found to be $\log N_{O VII} (\text{cm}^{-2}) = 16.37^{+0.07}_{-0.08}$, somewhat lower than, but consistent with that noted above, and with much smaller errors.

In the Mrk 509 spectrum, we could determine the $z = 0$ Ne IX column density accurately (log $N_{Ne IX} (\text{cm}^{-2}) = 15.85 \pm 0.2$) even though the line was not individually detected.

The velocity dispersion parameter obtained with PHASE fitting is $b = 74^{+89}_{-74} \text{ km s}^{-1}$ (where the lower limit is pegged at the hard limit) and temperature $\log(T/k) = 6.33 \pm 0.16$. The $b$-parameter is not well constrained, but is consistent with the value obtained from using the Kα and Kβ line ratio noted above.

We could not constrain the metallicity of the gas independently in PHASE; assuming $Z = 0.3 Z_{\odot}$, the fit gives total equivalent hydrogen column density of $N_H = 2.15 \times 10^{20} \text{ cm}^{-2}$ (Table 4).

### 5. Results

While the strength of an absorption line depends on the ionic column density of the intervening gas ($N_H = \mu n_e R$, where $n_e$ is the electron density and $R$ is the pathlength, and $\mu$ is the mean molecular weight), the emission is sensitive to the square of the number density (EM = $n_e^2 R$, assuming a constant density plasma). Therefore, a combination of absorption and emission measurements breaks the degeneracy and provides constraints on physical properties such as pathlength and density of the absorbing/emitting gas.

From the PHASE model of $z = 0$ absorption lines and galactic halo emission model, we constrained the temperature of the absorbing and emitting gas to $\log(T(K)) = 6.33 \pm 0.16$ and $\log(T(K)) = 6.33 \pm 0.01$ respectively. Since the temperature of the absorbing and emitting gas is the same, it is reasonable to assume that both absorption and emission arise in the same plasma. We can now combine the column density and emission measure to extract physical properties of the absorbing/emitting warm-hot gas.

#### 5.1. Uniform Density Halo Model

Assuming that absorbing/emitting plasma has a constant density, we derive the density of

$$n_e = (6.6^{+1.7}_{-1.2}) \times 10^{-4} \left( \frac{0.5}{f_{O VII}} \right)^{-1} \text{ cm}^{-3} \tag{1}$$

and the pathlength of:

$$R = (126^{+41}_{-41}) \left( \frac{8.51 \times 10^{-4}}{A_\odot/A_H} \right) \left( \frac{0.5}{f_{O VII}} \right)^2 \left( \frac{0.3 Z_{\odot}}{Z} \right) \text{ kpc} \tag{2}$$

where the solar oxygen abundance of $A_\odot/A_H = 8.51 \times 10^{-4}$ is from Anders & Grevesse (1989) and $f_{O VII}$ is the ionization fraction of O VII. Simulations of the CGM around disk galaxies (Toft et al. 2002; Sommer-Larsen 2006) suggest that the mean metallicity of gas is $Z = 0.2 \pm 0.1 Z_{\odot}$. These values of metallicities are also consistent with observational results for the outskirts of groups (Rasmussen et al. 2009), clusters of...
galaxies (Tamura et al. 2004), and external galaxies (Bogdan et al. 2013b; Anderson et al. 2016). Because pathlength is inversely proportional to the metallicity (Equation (2)), lower values of metallicity correspond to larger pathlengths and consequently higher masses. Thus to be conservative and consistent with our Papers I and II, we used $\epsilon = 0.3 Z_e$.

The CGM parameters along just one sightline are presented here, and as noted in Section 1 the Milky Way CGM is likely anisotropic. Thus we cannot determine the CGM mass using parameters of only one sightline. Nonetheless, for the sake of comparison with another density distribution such as the $\beta$-model discussed below, we will assume a spherical symmetry and covering fraction of 1 of the warm-hot CGM gas with density and pathlength calculated above. This leads to the mass of the plasma $= 5.4 \times 10^{10} M_\odot$. For a covering factor of 0.72 used in Paper I, the mass is $= 3.9 \times 10^{10} M_\odot$. This is lower than the mass derived in Paper I ($= 2.3 \times 10^{11} M_\odot$); this is largely due to the unusually high EM along this sightline.

![Figure 5](image_url)

**Table 3**

| $\lambda_{obs}$ | EW (mA) | EW (mA) | Ion Name | $\lambda_{rest}$ (Å) |
|-----------------|---------|---------|-----------|----------------------|
| 21.61 ± 0.01    | 19.5 ± 4.8 | 23.9 ± 5.0 | O VII $\alpha$ | 21.602 |
| 18.62 ± 0.01    | 11.0 ± 4.0 | 11.7 ± 4.1 | O VII $\beta$ | 18.627 |
| 18.97 ± 0.01    | 12.0 ± 3.4 | 10.3 ± 4.3 | O VIII $\alpha$ | 18.969 |

**Table 4**

| Parameter | $z = 0$ Component |
|-----------|-------------------|
| $\log T$ (K) | 6.33 ± 0.16 |
| $\log N_H$ (cm$^{-2}$) | 20.33 ± 0.19a |
| $b$ km s$^{-1}$ | 74 ± 80 |
| $N$(Ovii) cm$^{-2}$ | $(2.35 ± 0.4) \times 10^{16}$ |
| $N$(Oviii) cm$^{-2}$ | $(1.81 ± 0.5) \times 10^{16}$ |
| $(N_{Ne})_{cm}^{}$ | $(7.14 ± 1.8) \times 10^{15}$ |

**Note.**

- $^{a}$ Assuming $Z = 0.3 Z_e$.

**Note.**

- $^{a}$ Mrk 509 Chandra LETG measurement.
which leads to larger density and smaller pathlength (Section 7).

### 5.2. β-model

Above (and also in Papers I and II), we assumed a constant density plasma, but the Galactic halo likely has a non-uniform density profile. Since the EM is biased toward high density, this could affect the results. A realistic halo is likely to have some density profile that falls with radius, so we should use a model with a reasonable density distribution and compare the model predictions to observations for obtaining constraints on the structure of the Galactic CGM.

The distribution of the warm-hot gas around several elliptical galaxies follows a beta-model profile in which the density is high in the center and falls off with radius (Mathur et al. 2008; Forbes et al. 2012); gas in clusters and groups of galaxies also follows similar profile (Jones & Forman 1984; Forman et al. 1985; Mulchaey & Zabludoff 1998). Anderson & Bregman (2011), Anderson et al. (2016), and Dai et al. (2012) used the β model to fit the radial surface brightness profile of hot halo gas around spiral galaxies.

The β-model is given by

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

where $r$ is the galactocentric radius, $n_0$ is the central density, $r_c$ is the core radius, and $\beta$ describes the shape. We have two measurements (column density and emission measure) and three unknowns ($n_0$, $r_c$, and $\beta$), so the parameters are degenerate. We first assumed $\beta = 0.5$ in our calculations and then varied the value of $\beta$ to see its effect on the results.

Our sightline to Mrk 509 passes through the Milky Way halo along the direction fixed by the Galactic coordinates ($l = 35^\circ 097, b = -29^\circ 85$), and our measurements of absorption and emission are along this sightline. Thus we first converted $n(r)$ to $n(s)$, where $s$ is the pathlength along the sightline. We assumed that we are at 8 kpc from the Galactic center and the virial radius of the Galaxy is 250 kpc, providing the maximum pathlength for integration. Using Mathematica, we then determined the values of $n_0$ and $r_c$, which are consistent with both the absorption column density ($N_H$) and the emission measure (EM).

The results are shown in Figure 7, where $n_0/\mu$ is plotted on the X-axis and $r_c$ on the Y-axis. Solid lines mark the best-fit and error contours for the observed column density and the dash lines are the same for the emission measure. The central density is constrained to be between $n_0 = 2.8 - 6.0 \times 10^{-4} \text{ cm}^{-3}$. For the core radius, however, we only have a lower limit $r_c \geq 40 \text{ kpc}$. For larger values of $\beta$, the lower limit on $r_c$ increases $(r_c \geq 50 \text{ kpc} \text{ for } \beta = 0.6)$, the upper limit on $n_0$ becomes slightly smaller $(n_0 = 5.8 \times 10^{-4} \text{ cm}^{-3} \text{ for } \beta = 0.6)$, but the lower limit on $n_0$ remains the same.

For $r_c = 40 \text{ kpc}$ (lower limit) and the corresponding $n_0 = 0.0006 \text{ cm}^{-2}$, the mass within the virial radius of 250 kpc is $3.2 \times 10^{10} \text{ M}_\odot$. For the lower limit of density $(n_0 = 0.00028 \text{ cm}^{-3})$ and the corresponding $r_c = 280 \text{ kpc}$, the mass is $9.98 \times 10^{10} \text{ M}_\odot$ (Table 5).

### 6. Comparison with External Galaxies

Similar to the Milky Way, other spiral galaxies should also have massive, extended reservoirs of ionized hot gas in the CGM. X-ray absorption line spectroscopy of galactic halos is difficult because only a small number of AGNs are bright enough, but several authors have studied the halos around spiral galaxies in emission. Most of these, however, are massive spiral galaxies, not Milky-Way-types.

Anderson et al. (2016) and Dai et al. (2012) detected hot gaseous halos in emission around the giant spiral galaxies NGC 1961 and UGC 12591, extending to 40-50 and 110 kpc respectively. These authors estimate the mass of their hot halo gas to be $5 \times 10^9 \text{ M}_\odot$ and $3.9 \times 10^9 \text{ M}_\odot$ respectively, within a radius of 50 kpc, and when density profiles are extrapolated to
virial radii of 500 kpc, the implied hot halo mass is $1-3 \times 10^{13} M_\odot$. Similarly Bogdan et al. (2013b, 2013a) have detected X-ray emission around two other spiral galaxies NGC 4631 and NGC 4626 and estimated the hot X-ray gas mass within ~60 kpc to be $1.2 \times 10^{10} M_\odot$ and $9.1 \times 10^{11} M_\odot$, respectively. Though the detected masses in hot halos of these galaxies are significant, it is not a major contributor to the galactic missing baryons because these are very massive galaxies; it falls short by an order of magnitude.

Around low-mass (Milky-Way-type) spiral galaxies, the picture is a bit different. Strickland et al. (2004) using Chandra observations found diffuse X-ray emitting halos in eight nearby ($D < 17$ Mpc) galaxies, extending to radii of 18 kpc. Since these are very nearby galaxies, the Chandra field of view probes only a 20 kpc region around the galaxies. With Suzaku observation, Yamasaki et al. (2009) confirmed the X-ray halo of NGC 4631 ($D \sim 8$ Mpc) extending out to about 10 kpc from the galactic disk. With XMM-Newton, Tullmann et al. (2006) detect the diffuse gaseous X-ray halos extended over a range of 4-10 kpc around nine nearby star-forming edge-on spiral galaxies. However, these observations (8–55 ks) are not deep enough to detect soft X-ray halos extending out to large radii.

Recently, Bogdan et al. (2015) searched for the hot coronae around lower mass spiral galaxies with stellar masses of $(0.7–2.0) \times 10^{11} M_\odot$ using Chandra ACIS observations. They did not detect a statistically significant hot corona around any of their sample galaxies. The authors noted that the low effective area of Chandra ACIS-I or a smaller field of view of ACIS-S might be reasons for the non-detections.

Thus we see that the observations of Milky-Way-type galaxies were either too shallow or with too small a field of view to detect extended, massive CGMs. Extended, massive CGMs are detected around massive spiral galaxies, but they do not contribute significantly to the baryon budget. Why some spiral galaxies have a large fraction of baryons in their CGM and some do not? The extent of the CGM in a galaxy and the fraction of missing baryons it contains may depend on several properties of a galaxy: stellar mass (Bogdan et al. 2015), specific star formation rate (Tumlinson et al. 2011), or dark-matter halo mass (Oppenheimer et al. 2016). All three reasons could be related as galaxies with higher mass have substantially lower specific star formation rates (Damen et al. 2009; Genel et al. 2014) and feedback may affect both the star formation rate and stellar mass. Radio-mode feedback may expel gas from a galaxy leading to both smaller stellar mass and less massive CGM (Bogdan et al. 2015). In the simulations of Roca-Fabrega et al. (2016), the fraction of hot gas mass in more massive galaxies is indeed smaller.

### 7. Discussion

In Paper I we assumed a constant density model to determine the CGM parameters of the Milky Way. We found a huge reservoir of baryonic mass of over $6 \times 10^{10} M_\odot$. This result was criticized by some who argued that the mass is overestimated because of the assumption of constant density (Wang & Yao 2012 also see Mathur 2012 and references therein). In Paper II we made logical arguments and showed mathematically that that is not the case. On the contrary, any non-uniform density profile with density falling with radius would necessarily lead to larger mass estimates. Here we confirm our arguments by comparing the constant density model with a $\beta$-model. Even the lower limit on mass is comparable to that with a constant density (see Table 5), and is over twice as much for the lower limit on the central density.

CGMs also likely have a radial temperature profile, but we do not have observational constraints to determine the temperature profile, so we assume constant temperature. With more sightlines, we will have more observables to determine the temperature profile. We note that Faerman et al. (2016) also assume that the mean gas temperature is constant as a function of radius in their theoretical model.

Another matter of contention in the literature is the location of the warm-hot gas, whether in the ISM of the Galactic disk, the CGM, or beyond. In Paper II, we argued that the Galactic ISM cannot be the major contributor to the $z = 0$ absorption lines. Here we constrain the core radius of the absorbing/emitting gas to be over 40 kpc, clearly ruling out the ISM origin and placing the gas in the CGM of the Galaxy (see alsoNicastro et al. 2016).

In Paper I, we used sky-average values of column density and emission measure, with $\log N_{\text{O VII}} \text{ (cm}^{-2}) = 16.19 \pm 0.08$ and $\text{EM} = 0.003 \text{ cm}^{-6} \text{ pc}$. What we find here, along the $\text{Mrk 509}$ sightline is $\log N_{\text{O VII}} \text{ (cm}^{-2}) = 16.37 \pm 0.08$ and $\text{EM} = 0.0165 \pm 0.0008 \pm 0.0006 \text{ cm}^{-6} \text{ pc}$. Thus, along the $\text{Mrk 509}$ sightline the $\text{O VII}$ column density is larger by 0.2 dex and the emission measure is larger by a factor of five. As a result, the density along this sightline is larger than average and the pathlength is smaller than average (for a constant density model as in Paper I). The parameters along the two sightlines presented in Paper II are $\log N_{\text{O VII}} \text{ (cm}^{-2}) = 16.22 \pm 0.23$ and $16.09 \pm 0.19$, and $\text{EM} = 0.0025 \pm 0.0003 \pm 0.0005 \text{ cm}^{-6} \text{ pc}$ and $0.0042 \pm 0.0003 \pm 0.0007 \text{ cm}^{-6} \text{ pc}$, respectively. This underscores the value of measuring absorption and emission along the same sightline to derive the physical properties of the warm-hot gas. We should do so for several sightlines through the MW-CGM to understand its average properties and anisotropy. Part of the anisotropy would arise from our location in the Galaxy as different sightlines would probe different parts of the Galactic CGM (Nicastro et al. 2016, and references therein). However, part of the anisotropy could also be intrinsic, as suggested by simulations of Roca-Fabrega et al. (2016). We will investigate this further with more sightlines with absorption and emission observations.

In Figure 8, we have plotted the $\beta$-model profile in the $\text{Mrk 509}$ direction together with the profile obtained by Fang et al. (2013), which is the Maller & Bullock (2004) profile. The Maller & Bullock profile specifies the density and temperature

| Component | Mass ($M_\odot$) |
|-----------|-----------------|
| Virial Mass | $1 \times 10^{13} M_\odot$ |
| Baryonic Mass | $1.7 \times 10^{11} M_\odot$ |
| Stellar + cold gas mass | $6 \times 10^{10} M_\odot$ |
| Missing Baryonic Mass | $1.1 \times 10^{13} M_\odot$ |

Average: uniform density (Paper-I) $> 6.1 \times 10^{10} M_\odot$.
This paper: uniform density $3.9 \times 10^{10} M_\odot$.
This paper: $\beta$ model $3.2-10 \times 10^{10} M_\odot$.

Notes.

$^a$ Calculated using cosmological baryon fraction of $\Omega_b = 0.17$ measured by the Wilkinson Microwave Anisotropy Probe (Dunkley et al. 2009).

$^b$ (Sommer-Larsen 2006).
Figure 8. $\beta$-profiles deduced from this work are shown with solid lines. The blue and red curves correspond to the upper and lower limits on density, respectively. The dashed black curve is the Maller & Bullock profile from Fang et al. (2013).

profiles for adiabatic hot gas with polytropic index $n = 5/3$ in hydrostatic equilibrium in an NFW dark-matter potential well. We see that shape of their profile is similar to our $\beta$-model profile for the lower limit of $r_c$, though our density is higher. Our lower limit on the central density is similar to theirs, but our corresponding profile is flatter. Given that the $\beta$-model we present here is deduced from only one sightline, and that also with an unusually high emission measure, the differences are not surprising.

Recently, Faerman et al. (2017) presented an analytic phenomenological model for warm-hot CGMs of L* galaxies. The hot gas is in hydrostatic equilibrium in a Milky Way gravitational potential. They find the median temperature of the hot gas to be $1.8 \times 10^{5}$ K, similar to what we find for the MW CGM. They also find the CGM to be extended, slightly beyond the virial radius, and massive with $1.35 \times 10^{11} M_{\odot}$, accounting for missing baryons in galaxies in the local universe. These results, as well as those from Fang et al. (2013) and other theoretical models noted in Section 1, provide strong support for our results on the Milky Way CGM.

In these works, the density distribution of the warm-hot gas is presented as a smooth profile. It is possible, however, that the gas is clumpy and this could have a noticeable impact on model fits because emission measures scale with $n^2$, while absorption scales with $n$. Recent theoretical simulations by Roca-Fabregas et al. (2016) show the presence of filamentary structure in the CGM. In future work, when we have emission and absorption measurements along several directions, we will include clumping factors $(n^2) / \langle n \rangle^2$ in our models to assess their impact on our interpretation, and we will look at hydrodynamic simulations of galaxy formation for guidance about expected levels of clumping and anisotropy. We note, however, that in contrast to the cool CGM component traced by high-velocity HI clouds, we expect the hot gas component detectable in X-ray data to be relatively smooth (e.g., Stocke et al. 2013). Faerman et al. (2017) include clumping in their models, but the higher density clumped gas is cooler, traced by OVI and the hotter gas, probed by O VII and O VIII is indeed smooth.

To conclude, the hot gaseous CGM of the Milky Way appears to be diffuse and extended. The CGM is clearly anisotropic as shown by the distributions of both absorption and emission measurements. We have determined the properties of the hot CGM by combining absorption and emission measurements along three sightlines, two of which were presented in Paper II and one is presented in this paper. Additionally, in this paper, we have fitted the absorption spectrum with a theoretical collisional-ionization model, obtaining tight constraints on the temperature of the gas. We have also added a $\beta$-model density profile and show that the CGM remains diffuse, extended, and massive. Our results are consistent with numerical simulations as well as analytic models and suggest that a large fraction of the MW missing baryons reside in its hot CGM.

This work is supported in part by the NASA grant NNX16AF49G to S.M. Y.K. acknowledges support from grant DGAPA PAIPIT IN104215 and CONACYT grant168519.

References
Anders, E., & Grevesse, N. 1989, GeCoA, 53, 197A
Anderson, M. E., & Bregman, J. N. 2010, ApJ, 714, 320
Anderson, M. E., & Bregman, J. N. 2011, ApJ, 737, 22
Anderson, M. E., Churazov, E., & Bregman, J. N. 2016, MNRAS, 455, 222
Bogdan, A., Forman, W. R., Kraft, R. P., & Jones, C. 2013a, ApJ, 772, 98
Bogdan, A., Forman, W. R., Vogelsberger, M., et al. 2013b, ApJ, 772, 97
Bogdan, A., Vogelsberger, M., Kraft, R. P., et al. 2015, ApJ, 804, 72
Bregman, J. N. 2007, ARA&A, 45, 221
Dai, X., Anderson, M. E., Bregman, J. N., & Miller, J. M. 2012, ApJ, 755, 107
Damen, M., Labbe, I., Franx, M., et al. 2009, ApJ, 690, 937
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Dunkley, J., Komatsu, E., Nolta, M. R., et al. 2009, ApJS, 180, 306
Faerman, Y., Sternberg, A., & McKee, C. F. 2017, ApJ, 835, 52
Fang, T., Baute, D., Bullock, J., & Ma, R. 2013, ApJS, 217, 21
Fang, T. T., Bullock, J., & Boylan-Kolchin, M. 2013, ApJ, 762, 20
Fang, T. T., Canizares, C. R., & Wolfire, M. 2006, ApJ, 644, 174
Feldmann, R., Hooper, D., & Gnedin, N. Y. 2012, ApJ, 763, 21
Forbes, D. A., Ponnam, T., & O'Sullivan, E. 2012, MNRAS, 425, 66
Ford, A. B., Oppenheimer, B. D., Dave, R., et al. 2013, MNRAS, 432, 89
Forman, W., Jones, C., & Tucker, W. 1985, ApJ, 293, 102
Galeazzi, M., Gupta, A., Covey, K., & Usinor, E. 2007, ApJ, 658, 1081
Genel, S., Vogelsberger, M., Springel, V., et al. 2014, MNRAS, 445, 175
Gupta, A., Galeazzi, M., Koutroumpa, D., Smith, R., & Lallement, R. 2009, ApJ, 707, 644
Gupta, A., Mathur, S., Galeazzi, M., & Kronold, Y. 2014, Ap&SS, 352, 775
Gupta, A., Mathur, S., Kronold, Y., Nicolato, F., & Galeazzi, M. 2012, ApJ, 760L, 8
Henley, D. B., & Shelton, R. L. 2008, ApJ, 676, 335
Henley, D. B., Shelton, R. L., & Kunz, K. D. 2007, ApJ, 661, 304
Henley, D. B., Shelton, R. L., Kwak, K., Joung, M. R., & Mac Low, M. 2010, ApJ, 723, 935
Ishisaki, Y., Maeda, Y., Fujimoto, R., et al. 2007, PASJ, 59, 113
Jones, C., & Forman, W. 1984, ApJ, 276, 38
Kaasra, J. S., Elviro, J., Arav, N., et al. 2014, A&A, 570, 73
Krongold, Y., Nicolato, F., Brichkhouse, N. S., et al. 2003, ApJ, 597, 832
Kuntz, K. D., & Snowden, S. L. 2008, A&A, 478, 575
Maller, A. H., & Bullock, J. S. 2004, MNRAS, 355, 694
Mathur, S. 2012, arXiv:1211.3137
Mathur, S., Sivakoff, G. R., Williams, R. J., & Nicastro, F. 2008, Ap&SS, 315, 93
Miller, M. J., & Bregman, J. N. 2013, ApJ, 770, 118
Miller, M. J., Hodges-Kluck, E. J., & Bregman, J. N. 2016, ApJ, 818, 112
Mitsuishi, I., Gupta, A., Yamasaki, N. Y., et al. 2012, PASJ, 64, 18
Malchaey, J. S., & Zabludoff, A. I. 1998, ApJ, 496, 73
Nicastro, F., Senator, F., Gupta, A., et al. 2016, MNRAS, 457, 676
Nicastro, F., Senatore, F., Krongold, Y., Mathur, S., & Elvis, M. 2016, *ApJ*, 828, 12
Nicastro, F., Zezas, A., Drake, J., et al. 2002, *ApJ*, 573, 157
Oppenheimer, B. D., Crain, R. A., Schaye, J., et al. 2016, *MNRAS*, 460, 2157
Peeples, M. S., Werk, J. K., Tumlinson, J., et al. 2014, *ApJ*, 786, 54
Rasmussen, J., Sommer-Larsen, J., Pedersen, K., et al. 2009, *ApJ*, 697, 79
Roca-Fabrega, S., Valenzuela, O., Colin, P., et al. 2016, *ApJ*, 824, 94
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, *ApJ*, 588, 65
Smith, R. K., Bautz, M. W., Edgar, R. J., et al. 2007, *PASJ*, 59, 141
Snowden, S. L., Freyberg, M. J., Kuntz, K. D., & Sanders, W. T. 2000, *ApJS*, 128, 171
Sommer-Larsen, J. 2006, *ApJL*, 644, L1
Simson, G. S., Brook, C., Prochaska, J. X., et al. 2012, *MNRAS*, 425, 1270
Stocke, J. T., Keeney, B. A., Danforth, C. W., et al. 2013, *ApJ*, 763, 148
Strickland, D. K., Heckman, T. M., Colbert, E. J. M., Hoopes, C. G., & Weaver, K. A. 2004, *ApJS*, 151, 193
Tamura, T., Kaastra, J. S., den Herder, J., et al. 2004, *A&A*, 420, 135
Taw, N., Hayashida, K., Nagai, M., et al. 2008, *PASI*, 60S, 11
Toft, S., Rasmussen, J., Sommer-Larsen, J., & Pedersen, K. 2002, *MNRAS*, 335, 799
Tullmann, R., Pietsch, W., Rossa, J., Breitschafter, D., & Dettmar, R. J. 2006, *A&A*, 448, 43
Tumlinson, J., Thom, C., Werk, J. K., et al. 2011, *Sci*, 334, 948
Vogelsberger, M., Genel, S., Springel, V., et al. 2014a, *MNRAS*, 444, 151
Vogelsberger, M., Zavala, J., Simpson, C., et al. 2014b, *MNRAS*, 444, 368
Wang, Q. D., & Yao, Y. 2012, arXiv:1211.4834
Wang, Q. D., Yao, Y., Tripp, T. M., et al. 2005, *ApJ*, 635, 386
Williams, R. J., Mathur, S., Nicastro, F., et al. 2005, *ApJ*, 631, 856
Yamasaki, N. Y., Sato, K., Mitsuda, K., et al. 2009, *PASJ*, 61, 291
Yoshino, T., Mitsuda, K., Yamasaki, N. Y., et al. 2009, *PASJ*, 61, 805