HIGH RESOLUTION X-RAY SPECTROSCOPY OF THE LOCAL HOT GAS ALONG THE 3C 273 SIGHTLINE

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ABSTRACT
X-ray observations of highly ionized metal absorption lines at $z = 0$ provide critical information on the hot gas distribution in and around the Milky Way. We present a study of more than 10 yr of Chandra and XMM-Newton observations of 3C 273, one of the brightest extragalactic X-ray sources. Compared with previous works, we obtain much tighter constraints on the physical properties of the X-ray absorber. We also find a large, non-thermal velocity at $\sim 100$–$150$ km s$^{-1}$, the main reason for the higher line equivalent width when compared with other sightlines. Using joint analysis with X-ray emission and ultraviolet observations, we derive a size of $5$–$15$ kpc and a temperature of $(1.5$–$1.8) \times 10^6$ K for the X-ray absorber. The 3C 273 sightline passes through a number of Galactic structures, including radio loops I and IV, the North Polar Spur, and the neighborhood of the newly discovered “Fermi bubbles.” We argue that the X-ray absorber is unlikely to be associated with the nearby radio loops I and IV; however, the non-thermal velocity can be naturally explained as the result of the expansion of the “Fermi bubbles.” Our data imply a shock-expansion velocity of $200$–$300$ km s$^{-1}$. Our study indicates a likely complex environment for the production of the Galactic X-ray absorbers along different sightlines, and highlights the significance of probing galactic feedback with high resolution X-ray spectroscopy.

Key words: ISM: general – quasars: absorption lines – quasars: individual (3C 273, PKS 2155–304, Mkn 421) – X-rays: ISM

Online-only material: color figures

1. INTRODUCTION
Since the launch of the Chandra and XMM-Newton X-ray telescopes, the onboard high resolution X-ray spectrometers have opened a new window to study the interstellar medium (ISM) in our Galaxy. Numerous absorption features, produced by metal species with ionization stages ranging from neutral to hydrogen-like, were detected in the X-ray spectra of bright background sources such as the active galactic nuclei (AGNs) and Galactic X-ray binaries (XRBs; see, e.g., Nicastro et al. 2002; Fang et al. 2003; Rasmussen et al. 2003; Yao & Wang 2005; Williams et al. 2005; Bregman & Lloyd-Davies 2007; Pinto et al. 2010, 2012; Hagihara et al. 2010; Gorczyca et al. 2013; Liao et al. 2013). Due to the distance constraint, most XRBs can only probe the ISM within the Galactic disk, while AGNs can help us study the ISM that may be distributed beyond the disk and extend into the Galactic halo. AGN study of the Milky Way ISM, however, is constrained by the brightness of the background sources. The most prominent absorption line produced by highly ionized metals at $z = 0$ is the O vii K$\alpha$ transition at 21.6 Å. So far, only a handful of targets are bright enough to detect other absorption line features, especially the crucial O vii K$\beta$ transition at 18.63 Å, and enable a diagnosis of X-ray absorbing gas using high resolution X-ray spectroscopy.

Mkn 421, PKS 2155, and 3C 273 are the three brightest extragalactic X-ray sources that have been repeatedly observed with Chandra and XMM-Newton. Despite sampling very different directions of Mkn 421 and PKS 2155–304, the two sightlines display a very similar distribution of hot gas (see Williams et al. 2005, 2007; Gupta et al. 2012). The X-ray observation of the 3C 273 sightline, on the other hand, showed a quite different picture. Previous studies indicated that the detected O vii K$\alpha$ line equivalent width (EW) along the 3C 273 sightline is about two times higher (see, e.g., Fang et al. 2003; Rasmussen et al. 2003). By comparing with the Mkn 421 sightline, Yao & Wang (2007a) concluded that the X-ray emission/absorption along the 3C 273 sightline line is enhanced by a Galactic central soft X-ray enhancement component.

The sightline toward 3C 273 passes through part of the sky that is enriched with supernova (SN) activities (see the next section for details). Furthermore, since the early work of Yao & Wang (2007a), two giant gamma-ray bubbles (“Fermi bubbles,” see Su et al. 2010) have been discovered in the Galactic center, and the 3C 273 sightline passes through the edge of the northern bubble. Also, new data from both X-ray emission and absorption observations along this sightline were collected. The goal of this Letter is therefore to investigate the role of the Galactic structures along the 3C 273 sightline by making use of the latest data.

Our Letter is organized as follows. In Section 2 we give a detailed description of the Galactic structures along the 3C 273 sightline. We perform Chandra data reduction and analysis in Section 3. In Section 4 we discuss the implication of our results by combining the results from the X-ray absorption observations with those from UV and X-ray emission observations. The last section gives the summary and discussion.

2. THE SIGHTLINE TOWARD 3C 273
The 3C 273 sightline passes through several complicated Galactic structures (see, e.g., Savage et al. 1993; Sembach et al. 1997, 2001). One of the most prominent structures in the radio continuum sky is the giant radio loops that cover a significant fraction of the sky. These radio loops are believed to be superbubble structures created by a series of SN explosion. The 3C 273 sightline passes through the edges of two known radio loops, Loops I and IV (see Figure 1 for details). Loops I and IV are the result of a series of such explosions in the Sco-Cen region.
OB association (Berkhuijsen et al. 1971; Berkhuijsen 1973) and are about $\sim$130 and 210 pc away, respectively. In Figure 1 we plot the ROSAT $3/4$ keV all-sky survey map in Galactic coordinates (Snowden et al. 1995). The origin and location of the prominent X-ray feature, the North Polar Spur (NPS), are still unclear. It has been suggested that the NPS could be the result of the Loop I superbubble colliding with the Local Hot Bubble surrounding the Sun (see, e.g., Egger & Aschenbach 1995), or a more distant phenomenon near the Galactic central region (see, e.g., Sofue 2000; Bland-Hawthorn & Cohen 2003).

Recently, two large gamma-ray bubbles (“Fermi bubbles”), along with several large-scale structures, were discovered in the Fermi-LAT data (Su et al. 2010; see our Figure 1). The giant northern bubble extends to $b \sim 55^\circ$ ($\sim$10 kpc) above the Galactic plane with a width of $\sim$40$^\circ$ along the longitude direction. Next to the bubble is the northern arc (the two cyan dotted lines) that extends from $b$ $\sim$ 0 to nearly 60$^\circ$, coincident with the prominent NPS feature in the X-ray. Fermi data also revealed a giant loop-shape structure that aligns with Loop I. Recent studies indicated that the NPS may be related to the Fermi bubbles, in particular, the northern arc (see, e.g., Su et al. 2010; Guo & Mathews 2012; Kataoka et al. 2013). The 3C 273 sightline passes right through the outer loop-shaped structure as well as part of the region that may be associated with the northern arc and NPS. This sightline also passes through a region that is fairly close to the edge of the Fermi bubbles.

3. CHANDRA AND XMM-NEWTON OBSERVATIONS AND DATA REDUCTION

As a calibration source, 3C 273 ($z = 0.158, l = 289.95, b = 64:36$) has been observed many times with Chandra and XMM-Newton. We focus on the observations performed with the high resolution gratings on board Chandra and XMM-Newton for a combination of high spectral resolution and reasonable sensitivities. In particular, for Chandra we analyzed the data obtained with the medium energy gratings (MEGs) and low energy gratings (LEGs), with the Advanced CCD Imaging Spectrometer as the focal plane detector; for XMM-Newton we focused on the Reflecting Grating Spectrometer unit 1 (RGS1); the other RGS unit, RGS2, has a failed CCD in the crucial O vii line region, so we did not use the data taken by RGS2.

Between 2000 and 2012, there were a total of 12 observations taken with MEG, and 6 observations with LEG, with total exposure time of 294 ks and 174 ks, respectively. Each data set was analyzed following the standard procedure, with version 4.5 of the Chandra Interactive Analysis of Observations software. We co-added positive and negative first-order grating spectra to enhance the photon statistics. To simplify the spectral fitting, we also combined the 12 HETG observations and the 6 LETG observations to construct one MEG and one LEG spectrum.

For XMM-Newton over the same period, 20 observations of 3C 273 were performed with a total exposure of 769 ks. Standard data reduction process was applied using the XMM-Newton data analysis software SAS, version 12.0.1. We filtered periods that were impacted by high background events. Due to the large variation of the RGS1 response matrix between different observations, we cannot co-add all the data sets in the way that we adopted for the Chandra data sets. All the data sets have to be fitted simultaneously to avoid systematic errors (Rasmussen et al. 2007).

Using the X-ray spectral-fitting package XSPEC version 12.7.1, the broadband continuum can be well-fitted by a power law plus Galactic neutral hydrogen $N{\text{H}} = 1.79 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990) over 0.5–8.0 keV. We clearly detected highly ionized O vii and Ne ix K-series ($K\alpha$, $K\beta$),

1 See http://cxc.harvard.edu/ciao/threads/gspec.html
2 See http://xmm.esa.int/sas/
3 See http://heasarc.nasa.gov/xanadu/xspec/.
and O viii Kα transitions. For O vii Kα and Kβ transitions, we simultaneously fitted the LEG, MEG, and RGS1 data with a Voigt profile-based line model. Due to a failed CCD in RGS1 around the Ne ix line region and bad pixels in the RGS1 spectra around the O viii Kα region, for these two ion species we used the Chandra data only. The free parameters for this model are the line column density (N), the Doppler b parameter, and the redshift of the line center wavelength (see Buote et al. 2009 and Fang et al. 2010 for details). We also tied all these parameters together for the same ion but different transitions. In Table 1 we list all the measured and derived parameters. For the line EW, we estimated its error using Monte Carlo simulations (Fang et al. 2010). We cannot constrain the Doppler b parameter of the O viii Kα line, so we fixed the it at b = 129 km s\(^{-1}\), the best-fit value for the O vii line.

### 4. ANALYSIS

#### 4.1. Physical Properties Derived from X-Ray Absorption Observations

The line EW of an absorption line depends jointly on the ion column density and the Doppler b parameter. In Figure 2 we show the column density versus the Doppler b contour plot of the O vii Kα line of 3C 273, as well as comparison with other work. Yao & Wang (2007a) studied a subset of the Chandra data that we analyzed in this Letter. Although our results are largely consistent with theirs, compared with a total of \(\sim 400\) ks exposure in their work, better photon statistics has significantly improved the constraints on the key physical parameters. The measured 1σ range of the Doppler b parameter is 31 km s\(^{-1}\) < b < 46 km s\(^{-1}\) for Mkn 421 (Williams et al. 2005) and 35 km s\(^{-1}\) < b < 94 km s\(^{-1}\) for PKS 2155−304 (Williams et al. 2007). The column density in Yao & Wang (2007a) is somewhat lower than that of Williams et al. (2007), and we refer readers to Yao & Wang (2007b) for a detailed discussion of the likely causes. We find that while for these three sightlines the O vii column densities are similar on the order of (1−2) \(\times 10^{21}\) cm\(^{-2}\), the Doppler b parameter of 3C 273, 129\(^{+12}_{-7}\) km s\(^{-1}\), is significantly higher than those of PKS 2155−304 and Mkn 421, leading to a much higher line EW.

We now investigate the physical conditions of the X-ray absorber. A pure photoionization model is unlikely: previous modeling suggests that the observed column densities would require a typical intergalactic environment in which the path length of the absorber would be at \(\sim\)Mpc level (see, e.g., Collins et al. 2005; Williams et al. 2007). We also consider cases of collisional ionization. We adopted the ionization fractions calculated by Gnat & Sternberg (2007), and the temperature of the X-ray absorber can be nicely constrained at a narrow range between 1.5 \(\times 10^{6}\) K < T < 1.8 \(\times 10^{6}\) K, regardless of the metal abundance and whether or not the gas is in collisional ionization equilibrium (CIE).

It is interesting to note that assuming purely thermal broadening, this temperature would indicate a line width of \(b_{\text{th}} = 0.129 (T/\text{A})^{1/2}\), or 39 km s\(^{-1}\) < \(b_{\text{th}}\) < 43 km s\(^{-1}\). Here A is the atomic weight. This line width is fully consistent with the measurements of the Mkn 421 and PKS 2155−304 absorbers, implying the X-ray absorbers along these two sightlines are most likely thermally broadened (see, e.g., Hagihara et al. 2010). For 3C 273, the large Doppler b parameter suggests that non-thermal broadening plays a significant role. Since \(b^2 = b_{\text{th}}^2 + b_{\text{nt}}^2\), we derived a non-thermal velocity of \(b_{\text{nt}} \sim 100−150\) km s\(^{-1}\).

#### 4.2. Joint Analysis with X-Ray Emission and UV Observations

Recently, Henley & Shelton (2012) analyzed over thousands of XMM-Newton observations and measured the O viii emission line intensities along these sightlines. In their sample, we select two pointings that are spatially close to the 3C 273 sightline, and use the X-ray emission and absorption data jointly to derive the physical properties of the X-ray absorber. The two pointings are located at \((l, b) = (289.172, 63.713)\) (XMM Obs ID: 0110990201), and \((l, b) = (292.777, 62.619)\) (XMM Obs ID: 0203170301), about 1° and 3° away from the 3C 273 sightline, respectively. Their measured O vii (O viii) line intensities are 14.17 ± 1.27 and 13.68 ± 0.78, respectively. Here L.U. is the line unit (photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)). Since \(I_{\text{O vii}} \propto N_{\text{e}} N_{\text{H}}^2\) and \(N_{\text{O vii}} \propto L_{\text{obs}}\), we find \(n_e\) in the range of \((1.2−1.8) \times 10^{−3}\) cm\(^{-3}\) and \(L\) in the range \((5−15)\) kpc. Here \(n_e\) is the electron density and L is the size of the absorber. We also assume solar abundance.

Henley & Shelton (2012) measured the O viii emission line strength for these two pointings to be 2.46 ± 2.31 and 2.70 ± 1.81 L.U., respectively. Adopting the above estimated values, we find that the predicted O viii emission line intensity is \(I_{\text{O viii}} \sim 1.9\) L.U., consistent with results from Henley & Shelton (2012). We also estimate an O viii column density of

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**Table 1**

| ID       | \(\lambda_{\text{abs}}\) (Å) | \(v_{\text{obs}}\) (km s\(^{-1}\)) | b (km s\(^{-1}\)) | EW (mÅ) | \(\log N_{\text{vii}}\) (cm\(^{-2}\)) |
|----------|-----------------------------|-----------------------------|-----------------|--------|-----------------------------|
| O vii Kα | 21.602                      | 119\(^{+28}_{-27}\)         | 129\(^{+24}_{-18}\) | 25.65 ± 1.75 | 16.36 ± 0.10 |
| O vii Kβ | 18.629                      | ...                        | ...             | ...    | ...                         |
| Ne vii Kα| 13.447                      | −43\(^{+54}_{-58}\)        | 98\(^{+95}_{-54}\) | 12.05 ± 1.58 | 15.92\(^{+0.28}_{-0.14}\) |
| Ne viii Kβ| 11.547                     | ...                        | ...             | ...    | ...                         |
| O viii Kα| 18.969                      | 170\(^{+100}_{-90}\)       | 133             | 7.07 ± 2.50  | 15.77\(^{+0.15}_{-0.20}\) |

*Note.* All errors are quoted at the 1σ level unless otherwise stated.

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**Figure 2.** Contour plot of the O vii column density vs. the Doppler b parameter. The dashed and solid curves show the derived 1σ and 90% confidence contours for 3C 273, respectively, and the cross is the best-fit value. The hatched areas show the range of O vii column densities and the Doppler b parameters of 3C 273 and Mkn 421, measured in Yao & Wang (2007a). Note that they adopted a 90% error range. We also plot the contour for Mkn 421 (light gray square; Williams et al. 2005) and PKS 2155−304 (dark-gray ellipse; Williams et al. 2007) for comparison. (A color version of this figure is available in the online journal.)
of systems are remarkably similar between the Mkn 421 and PKS, which they used is consistent with the EM derived in Yao & Wang (2007a), in Figure 3.

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Column density ratio between O\textsc{vi} and O\textsc{vii} (black), Ne\textsc{x} and O\textsc{vii} (red), and O\textsc{v} and O\textsc{vii} (blue), as a function of temperature. The solid line is for the collisional ionization equilibrium (CIE). The dotted and dashed lines represent the isochoric cooling for 1 and 0.1 solar abundances, and the dot-dashed and dot-dot-dot-dashed lines are for the isobaric cooling. The thick line segments indicate the constraints from observations, and the vertical shaded area shows the temperature region that fits all observations.

(A color version of this figure is available in the online journal.)

log N(O\textsc{vii})(cm\textsuperscript{-2}) \sim 16.0. This is slightly larger than what we observed, but not by much. We estimate an emission measure (EM) of 0.02 cm\textsuperscript{-6} pc along this direction. Again, this value is consistent with the EM derived in Yao & Wang (2007a), in which they used ROSAT data.

Gupta et al. (2013) noted that while the absorption line systems are remarkably similar between the Mkn 421 and PKS 2155–304 sightlines, their X-ray EMs are different by a factor of $\sim 1.5$ ($\sim 0.0025$ cm\textsuperscript{-6} pc for Mkn 421 and $\sim 0.0042$ cm\textsuperscript{-6} pc for PKS 2155–304). They attributed this to the anisotropy of the circumgalactic medium, for which the Mkn 421 absorber has a much longer path length. Our estimated EM is much larger than both sightlines. Using their model the 3C 273 absorber would have a path length longer than the size of the Local Group. So it appears more likely that the 3C 273 absorber is local around the Galactic disk, with high density and strong non-thermal motion.

Far-Ultraviolet Spectroscopic Explorer observed 3C 273 for 43.3 ks on 2000 April 23 (see, e.g., Sembach et al. 2001, 2003; Wakker et al. 2003). The strong $\lambda 1031.93$ Å transition was clearly detected with three distinguishable components, with velocities at $-160$ to $+105$ to $+160$, as well as a broad wing at $160$ to $260$ km s$^{-1}$. We analyzed the three components and found, for the broad-wing component, that the same collisional ionization can explain the column density ratio between O\textsc{vii} and O\textsc{vi} very well (the blue lines in Figure 3). This component has an O\textsc{vi} column density of log N(O\textsc{vi}) $\sim 13.52$.

4.3. Possible Association with the “Fermi Bubbles”

The derived size of the X-ray absorber along the 3C 273 sightline, $\sim 5$–15 kpc, firmly puts the hot gas at the distant Galactic disk and possibly beyond, toward the direction of the Galactic central region. The X-ray absorber is unlikely to be associated with either radio loop I or IV, since both structures are within a few hundred pc; it is also unlikely to be linked to the giant loop-shaped structure seen in the Fermi-LAT data (see Figure 1). Also, the EM along this sightline is nearly an order of magnitude higher than those measured along the Mkn 421 and PKS 2155–304 sightlines. While Gupta et al. (2013) suggested the hot gas along these two sightlines is located at the distant Galactic halo with a path length of more than 100 kpc, it is unlikely to be the case for the 3C 273 sightline.

This sightline passes through part of the region that is associated with the NPS and the northern arc discovered in the Fermi-LAT data. Considering the proximity to the northern Fermi bubble, it is interesting to discuss the impact of the Fermi bubbles on the X-ray absorber along the 3C 273 sightline. It is unlikely that the X-ray absorption/emission is produced by the same material located within the Fermi bubbles: the temperature inside the bubble is hotter than $10^7$ K (Su et al. 2010), and all the ion species we detected in the X-ray would be completely ionized at this temperature.

However, such an X-ray absorber can be located in the region that is shock-impacted by the expansion of the Fermi northern bubble. X-ray observations of the edge of the Fermi bubble suggested a possible link with the NPS in the X-ray (Kataoka et al. 2013). Assuming an adiabatic gas of $\gamma = 5/3$, we estimated a shock Mach number of $\sim 2$ and a shock expansion velocity of $v_s = 2b_{\text{sh}} \sim 200$–300 km s$^{-1}$, following Kataoka et al. (2013). Such velocity would imply a bubble formation time of $(3$–$5) \times 10^7$ yr, assuming a bubble size of $\sim 10$ kpc. The shock temperature for an adiabatic expansion shock can be estimated as $T_s = 1.34 \times 10^5 (v_s / 100)^2 \sim 10^6$ K (Stocke et al. 2006) for $v_s = 300$ km s$^{-1}$, close to the temperature predicted by the UV and X-ray ion ratios in Figure 3.

5. SUMMARY AND DISCUSSION

In this Letter, we analyzed the Chandra and XMM-Newton grating observations of 3C 273, one of the brightest extragalactic X-ray sources, with a focus on the X-ray absorption lines produced by highly ionized metal species at $z = 0$. We summarize our findings below.

Using high resolution X-ray spectroscopy, we measured the physical properties of the X-ray absorber along the 3C 273 sightline. Our measured line properties are largely consistent with the previous work of Yao & Wang (2007a) based on a subset of the data used in this Letter, while better photon statistics allows us to put much tighter constraints. The column density ratios between O\textsc{vii}, O\textsc{viii}, and Ne\textsc{x} suggested a temperature of $(1.5$–$1.8) \times 10^6$ K of the X-ray absorbing gas. This gas is either in CIE, or cooling at constant density or constant pressure. A joint analysis with the X-ray emission data suggests that the X-ray absorber likely has a density of $(1.2$–$1.8) \times 10^{-3}$ cm$^{-3}$, with a linear size of $\sim 5$ to 15 kpc.

We compare the 3C 273 sightline with the sightlines of Mkn 421 and PKS 2155–304, which have similar or even better quality X-ray spectra. We find that the line EWs of 3C 273 are significantly higher than the other two sightlines. In particular, we find the large EWs are the result of a higher Doppler $b$ parameter rather than large column density. While the Doppler $b$ parameters of the X-ray absorbers detected in the Mkn 421 and PKS 2155–304 sightlines can be naturally explained by thermal broadening, a significant non-thermal component of $b_{\text{th}} \approx 100$–150 km s$^{-1}$ is present in the 3C 273 X-ray absorber.

Such non-thermal velocity has been suggested before as evidence of an outflow, possibly produced by stellar wind and SN activities in the Galactic center and the bulge region (Yao & Wang 2007a). Large-scale bipolar outflow was also proposed based on ROSAT and other observations (see Sofue 2000; Bland-Hawthorn & Cohen 2003). We suggest here an alternative that the non-thermal velocity we detected in the 3C 273 sightline can...
be naturally explained as the expansion of the newly discovered “Fermi bubble,” with a shock velocity of ~200–300 km s\(^{-1}\). The derived expansion velocity is much less than predictions from recent theoretical modeling (see Guo & Mathews 2012; Yang et al. 2013), as suggested by Kataoka et al. (2013).

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