Probing the Warm and Hot Absorbers along the Sightline of PG0052+251: Postprint

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Abstract

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Full Text

Preamble

Probing the Warm and Hot Absorbers along the Sightline of PG 0052+251

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Abstract

We analyze the absorption features in the public 73 ks XMM-Newton spectra of the Seyfert 1 galaxy PG 0052+251. Our analysis reveals the presence of a warm absorber (WA) intrinsic to the source and the hot circumgalactic medium at zero redshift. The identified WA is inflowing toward the central black hole, with a velocity shift of +156 km s^{-1}, showing strong O II and O III absorption lines, along with significant absorption of the spectral continuum at $\gtrsim$ 10 Å. The line of sight toward PG 0052+251 intersects the halo of M31 at an impact parameter of approximately 218 kpc. Several local ($z \sim 0$) absorption lines, like O VII, O VIII, and Ne IX, were detected. The derived hydrogen column density of the local hot gas is 2.2–2.6σ higher than those estimated by several models of the Galactic hot halo, suggesting a likely contribution from the M31 halo. We also find two absorption features at 24.305 Å and 21.410 Å, which are unlikely to be associated with the hot halos or the warm-hot intergalactic medium but imply the presence of an additional WA component with an outflow velocity of approximately −7000 km s^{-1}.

Key words: (galaxies:) quasars: individual (PG 0052+251) -(galaxies:) quasars: absorption lines -galaxies: halos -galaxies: individual (M31) -X-rays: galaxies

1. Introduction

Observing absorption features in the spectra of bright active galactic nuclei (AGNs) is an effective method for probing the properties of intervening gas between the light source and the observer. Around 50%–65% of nearby Seyfert galaxies exhibit intrinsic photoionized absorption lines in their soft X-ray spectra (e.g., Winter et al. 2012; Tombesi et al. 2013; Laha et al. 2014). These absorption lines mainly arise from warm absorbers (WAs) intrinsic to the AGNs. The WAs are usually outflowing gas with velocities of $\lesssim$ 2000 km s^{-1} (Laha et al. 2021) but also appear as inflowing gas in a few cases (e.g., Ebrero et al. 2011; Sanfrutos et al. 2018). The energies carried by WAs are typically inadequate to generate significant feedback to the host galaxies (e.g., Blustin et al. 2005; Ebrero et al. 2011; Zhou et al. 2024). However, the presence of WAs impacts the environment surrounding the central black holes (BHs) and plays a role in regulating their evolution.

Absorption features in AGN spectra may also be associated with ionized gas outside the host galaxies. In the soft X-ray band, this technique has been frequently employed to study the warm-hot intergalactic medium (e.g., Nicastro et al. 2005; Fang et al. 2010; Bonamente et al. 2016; Nicastro et al. 2018; Kovács et al. 2019) and the hot circumgalactic medium (CGM) in the Milky Way (MW, e.g., Bregman & Lloyd-Davies 2007; Yao & Wang 2007; Fang et al. 2015; Nicastro et al. 2016). Recently, the hot CGM in external L* galaxies has been robustly detected ($\gtrsim 4\sigma$) via X-ray absorption at approximately 0.5-0.6$R_{\rm vir}$ (Mathur et al. 2023; Nicastro et al. 2023), where $R_{\rm vir}$ is the virial radius. Absorption is the preferred method as detecting the hot CGM at $\gtrsim 0.2R_{\rm vir}$ is challenging using X-ray emission (e.g., Anderson et al. 2016; Bogdán et al. 2017; Comparat et al. 2022) and the thermal Sunyaev-Zel' dovich effect (tSZ effect, e.g., Bogdán et al. 2017; Singh et al. 2018; Bregman et al. 2022). However, due to the rarity of X-ray bright AGNs, finding an X-ray bright AGN behind a foreground galactic halo remains difficult (Mathur et al. 2021, 2023; Nicastro et al. 2023).

PG 0052+251 is a Seyfert 1 galaxy at a redshift of $z \sim 0.1545$. It was included in the sample compiled by Matzeu et al. (2023), which aimed to identify ultra-fast outflows (UFOs). Instead of detecting a UFO, a WA component was discovered as a byproduct in their analysis of the XMM-Newton/EPIC (European Photon Imaging Camera) spectra of PG 0052+251. This WA component has an ionization state of $\log \xi = 0.5$. Due to the limited spectral resolution of the CCD cameras, the authors were unable to constrain the velocity of the discovered WA. Additionally, the line of sight (LOS) of PG 0052+251 intersects the hot halo of M31 at an impact parameter of $R_{\rm imp} = 218$ kpc, offering a unique opportunity to study the hot CGM in M31 at a large radius via absorption.

In this paper, we analyze the public XMM-Newton spectra of PG 0052+251, aiming to probe the properties of the intrinsic WA and the hot CGM in M31 along the LOS. This paper is organized as follows. Sections 2 and 3 describe the data reduction and spectral analysis procedures, respectively. Through the analysis, we confirm the presence of the WA previously discovered by Matzeu et al. (2023) in the high-resolution RGS (Reflection Grating Spectrometer, den Herder et al. 2001) spectra and find that the WA is inflowing into the central black hole. In Section 4, we discuss the basic properties of the identified WA and present a potential signal from the hot CGM in M31. Throughout the paper, we adopt a virial radius of 260 kpc (Klypin et al. 2002; Beordo et al. 2024) and 300 kpc (van der Marel et al. 2012) for the MW and M31, respectively. The distance between the MW and M31 is assumed to be 780 kpc (Diaz et al. 2014; Kafle et al. 2018). All calculations are performed using a flat ΛCDM model, with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.70$, and $\Omega_M = 0.30$.

2. Data Reduction

PG 0052+251 was observed by XMM-Newton in 2005 and 2019, with a total exposure of 73 ks (Table 1). We adopted the RGS spectra from both observations to analyze the narrow absorption lines originating from the WA and the hot galactic halos at $z \sim 0$ (i.e., halos of the MW and M31). The raw data were reduced by the standard task `rgsproc` included in the Science Analysis Software (SAS), version 21.0.0. We generated the CCD light curves of both RGS units and applied 3σ clipping using the Chandra Interactive Analysis of Observations (CIAO) tool `deflare` to remove time intervals affected by soft flares (Mao et al. 2023). This step resulted in a total net exposure of 61.6 ks. Both the first- and second-order RGS spectra are adopted to enhance the statistic.

The EPIC-pn (Strüder et al. 2001) spectra were also extracted to extend the fitted energy band. This allows a more accurate constraint on the AGN continuum for a detailed analysis of spectral features. The EPIC-pn spectra were reduced using the SAS task `epproc`. Bad pixels were excluded by setting `FLAG == 0`, and the single and double events were selected (`PATTERN <= 4`) since the observations were not affected by the pile-up effect. A 40 circular region centered on the target was chosen to extract the source spectrum, and another 40 source-free region on the same chip was used for the background. The 10–12 keV light curve was employed to determine the good time intervals using 3σ clipping. The net exposure for the EPIC-pn spectra is 35.9 ks.

In comparing the two observations, the source maintains a consistent X-ray spectral shape, with its flux (0.3-10 keV) varying by only $\sim 10\%$. Therefore, we combined the spectra of the two observations for consequent analysis. We used the SAS tool `rgscombine` to combine the RGS spectra of each order, while the EPIC-pn spectra were combined using the tool `epicspeccombine`. To ensure an accurate analysis across different instruments and spectral orders, we cross-calibrated the RGS and EPIC-pn spectra to align their fluxes at a common wavelength band. The 7-8 Å spectral range was selected for this calibration, where no prominent spectral feature was observed. The RGS and EPIC-pn spectra were simultaneously fitted by power laws using a linked spectral index to determine the flux difference. We established the flux reference using the EPIC-pn spectrum, and the RGS first- and second-order spectra were rescaled by a factor of 1.055 and 1.028, respectively.

3. Spectral Analysis

In this section, we analyze the absorption lines associated with the WA and the hot galactic halos at $z \sim 0$. Spectral analysis was conducted using the SPEX package v3.08.00 (Kaastra et al. 1996; Kaastra et al. 2024), with state-of-the-art electron impact excitation data for hydrogen- and helium-like ions (Mao et al. 2022). The solar abundance table from Lodders et al. (2009) was adopted throughout the analysis unless otherwise mentioned. We rebinned the RGS spectra by a factor of three to avoid oversampling the data. The EPIC-pn spectrum was optimally rebinned using the SPEX command `obin` (Kaastra & Bleeker 2016). The best-fit results were derived by minimizing the C-statistic (Kaastra 2017). The uncertainties of the fitting parameters are determined using the error command in SPEX. Throughout the paper, we report the uncertainties and upper limits at the 1σ and 3σ significance levels, respectively.

3.1. Gaussian Line Fitting

In the first step, we adopt the Gaussian absorption profile (i.e., the Voigt profile model, `line`, in SPEX by setting the Lorentzian broadening to zero), searching for absorption lines originated from the WA and the local ($z \sim 0$) hot CGM. We restrict the analysis to the spectral range below 30 Å, as the source flux and the instrumental effective area rapidly decrease above this range. The WA discovered by Matzeu et al. (2023) has an ionization parameter of $\log \xi = 0.5$. At this ionization state, the most prominent absorption features are inner-shell O II and O III lines at 23.351 Å (Juett et al. 2004) and 23.065 Å (Gu et al. 2005), respectively, as predicted by the photoionization code `pion` in SPEX (Miller & Bregman 2015; Mehdipour et al. 2016; Mao et al. 2018). If the O II and O III lines originate from the AGN, their wavelengths will be redshifted to 26.959 Å and 26.629 Å in the observed spectra. As for the hot CGM, we focused the analysis on the transitions of Ne IX Heα (13.447 Å), O VII Heβ (18.629 Å), O VIII Lyα (18.969 Å), O VII Heα (21.602 Å), and N VII Lyα (24.781 Å). These ions are good tracers for hot gas with a temperature of a few million Kelvins (see, e.g., Bregman et al. 2015). The same transitions from the MW and M31 are overlapped in the RGS spectrum due to insufficient spectral resolution. Instead of separating the blended lines, we fitted each of them using a single Gaussian profile for the LOS total hot-gas absorption.

We adopted a 1-1.5 Å range segmental spectrum of RGS for each absorption feature, centering the line of interest within the segments. At $\lambda \gtrsim 25$ Å, a pronounced O VII emission bump intrinsic to the AGN affects the continuum modeling. Therefore, we used the 24.0–25.0 Å segment for analyzing the N VII Lyα line. The spectral continuum was modeled using a power law absorbed by the Galactic cold gas (`pow*absm`), with the Galactic hydrogen column density fixed at 3.96×10^{20} cm^{-2} (HI4PI Collaboration et al. 2016). For the local lines, we constrained the velocity shift within ± 1000 km s^{-1}, corresponding to the RGS resolution at the lines of interest. The velocity shift for the WA features was constrained within ± 2000 km s^{-1}. Line broadening was set within 20–600 km s^{-1}, which is adequate to explore all plausible solutions.

The best-fit line properties are listed in Table 2 . The uncertainty of equivalent width (EW), which is not a fitting parameter, was estimated by running 1000 Monte Carlo simulations (Appendix). The local O VII Heα and Heβ lines are insignificant, with the estimated EW uncertainties larger than their best-fit values. Hence, we provide their 3σ upper limits of EW based on the spectral quality (Fang et al. 2005).

Figure 1 [Figure 1: see original paper] shows the best-fit segmental spectra, with additionally rebinned data for display purposes. The Ne IX line was analyzed through joint fitting of the first- and second-order RGS spectra. We combine the two-order spectra using the SPEX tool `rgsfluxcombine` (Kaastra et al. 2011) and display the combined spectrum for plotting purposes.

In addition to the expected WA and CGM lines, we discovered a prominent absorption feature at 24.305 Å, with an EW of 76.6 ± 18.3 mÅ. A less significant feature is observed at 21.410 Å, with an EW of 43.6 ± 29.4 mÅ. While the precise nature of these two lines remains uncertain, they are likely the O VII Heα and O VIII Lyα lines associated with the AGN with an outflow velocity of approximately -7000 km s^{-1} (see Section 4.2). If the lines instead originate from an intervening hot-gas structure (e.g., galactic halo, Mathur et al. 2023; Nicastro et al. 2023; warm-hot intergalactic medium, Fang et al. 2010; Nicastro et al. 2018, 2022), the redshift of the absorbing system would be around $z \sim 0.125$.

3.2. Analysis Using Plasma Models

To estimate the plasma properties more accurately, we adopted the `pion` and `hot` (de Plaa et al. 2004; Steenbrugge et al. 2005) models in SPEX to analyze the gas absorption from the WA and the local hot CGM, respectively. The two models account for both absorption lines and edges produced by an intervening plasma in photoionization equilibrium (`pion`) and collisional ionization equilibrium (CIE, `hot`), respectively.

We jointly analyzed the \$ \$1-38 Å spectra of EPIC-pn and both orders of RGS. The spectral continuum was fitted using a power law (`pow`), a Comptonized component for the soft excess (`comt`), and a neutral reflection component (`refl`) for the 6.4 keV (AGN frame) Fe K emission feature (e.g., D' Ammando et al. 2008). Exponential cut-offs were applied to the power law. The high-energy cut-off of the target cannot be constrained in previous studies, but only a lower limit of > 137 keV was presented (Ricci et al. 2017; Pal et al. 2023). Therefore, we adopted a large value of 300 keV to the high-energy cut-off. The low-energy cut-off was set to 13.6 eV. We fixed the plasma temperature (kT_1) of `comt` at 0.28 keV according to the analysis of Williams et al. (2018). The ionizing continuum of the `refl` component was coupled with the power law. We adopted a `hot` component to model the Galactic neutral gas absorption, fixing the LOS hydrogen column at 3.96×10^{20} cm^{-2} (HI4PI Collaboration et al. 2016). The temperature of the Galactic neutral gas cannot be constrained by fitting the X-ray data of PG 0052+251.

Consequently, we examined the HI4PI spectrum for gas temperature. Assuming that the broadening of the observed H I 21 cm lines is purely due to thermal broadening, we calculated the average gas temperature using the column density of H I as the weight. This calculation resulted in an average temperature of approximately 3200 K (0.28 eV) for the LOS neutral gas, which was subsequently used in our X-ray continuum modeling. The other parameters were fixed at default values. The continuum modeling resulted in a fitting statistic of Cstat/DoF = 2279.8/1850, where DoF is the degree of freedom.

A pronounced emission feature can be observed at \$ \$25 Å (Figure 2 [Figure 2: see original paper]), attributed to the O VII triplet of a warm emitter (WE) intrinsic to the AGN (e.g., Porquet & Dubau 2000; Porquet et al. 2010). This feature consists of three lines, including the resonance line at a rest wavelength of 21.602 Å, the intercombination line at 21.803 Å, and the forbidden line at 22.101 Å. These lines are unresolved in the spectrum and appear as a single profile. We modeled this feature by applying three Gaussian emission profiles (`gaus`). The broadening of the lines was coupled since they originate from the same warm-emitting plasma. The velocity shift of the lines was fixed at zero, as the WE usually shows a fairly low speed (see, e.g., Mao et al. 2018, 2019b; Grafton-Waters et al. 2020). The intensity ratios between the triplet lines are good diagnostics of the plasma density, temperature, and ionizing mechanism (e.g., Gabriel & Jordan 1969; Porquet & Dubau 2000; Porquet et al. 2010; Mao et al. 2019a). In our modeling, we adopted ratios of $G = (f + i)/r = 4$ and $R = f/i = 2$, which link the intensities of the three lines under the assumption that the WE is purely photoionized with a typical density of 3×10^{10} cm^{-3} (e.g., Morales et al. 2002; Porquet et al. 2010). In the equations, r, i, and f are the intensities of the resonance, intercombination, and forbidden lines, respectively. Incorporating the WE improved the fitting by ΔCstat = 23.6 using two additional DoFs.

We adopted a photoionization component, `pion`, to model the WA features (e.g., Mao et al. 2017, 2019b; Wang et al. 2022). Following Matzeu et al. (2023), we fixed the turbulence velocity of `pion` at 100 km s^{-1} but fit the gas column density, ionization parameter, and velocity shift. The initial guess for the velocity shift of the WA component was set at 1000 km s^{-1} according to the result of Gaussian line analysis (Table 2). The other parameters of `pion` were set at default. An additional `hot` component was introduced to model the hot-CGM features at $z \sim 0$. To compare with previous results, we fixed the metal abundance at the commonly adopted value of $0.3Z_\odot$ (e.g., Miller & Bregman 2015; Li & Bregman 2017; Kaaret et al. 2020; Locatelli et al. 2024) and fit the column density, temperature, velocity shift, and broadening. Adding the absorption components improved the fitting by ΔCstat/ΔDoF = 16.5/7 (10.1/3 for the WA and 6.4/4 for the hot galactic halos). Our final model yielded a fitting statistic of Cstat/DoF = 2239.7/1841. The best-fit spectra and the corresponding model parameters are presented in Figure 2 [Figure 2: see original paper] and Table 3 , respectively. In Table 4 , we show the EWs of the hot CGM features obtained by the best-fit CIE (i.e., `hot`) model. The uncertainties in the EWs from the CIE modeling were derived using 2000 Monte Carlo simulations (Appendix).

4. Discussion

4.1. Properties of the Identified Warm Absorber

Through plasma model fitting, we identified a WA component in the RGS spectrum of PG 0052+251, with an ionization parameter of $\log \xi = 0.17$. This component severely absorbs the spectral continuum at $\lambda > 10$ Å (Figure 2 [Figure 2: see original paper]). The primary line features of this WA component are the O II and O III lines observed at $ $26.5–27 Å. Additionally, the best-fit model predicts lines at approximately 35.5-36 Å. In Matzeu et al. (2023), a similar WA component was detected in the EPIC spectra of PG 0052+251, with an ionization parameter of $\log \xi = 0.5$. The intrinsic continuum model used in their analysis is `pow + zbbody + zbbody` in XSPEC. Applying their best-fit continuum and using the flux command in XSPEC, we obtained an ionizing luminosity of $L_{\rm ion} = 1.6 \times 10^{45}$ erg s^{-1}, which is identical to the ionizing luminosity derived from our spectral modeling. The consistent ionizing luminosity and ionization parameter indicate that the WA identified in both studies corresponds to the same physical component. Unlike Matzeu et al. (2023), who fixed the WA velocity at zero, the high spectral resolution of RGS allows us to constrain the LOS velocity of the WA. The best-fit velocity shift is +156 km s^{-1}, indicating that the WA component is inflowing toward the central BH.

4.2. Potential WA Features in the RGS Spectrum

WAs usually consist of multiple components (e.g., Laha et al. 2014). We did observe other potential absorption features in the RGS spectrum, such as the lines at 24.305 Å with EW = 76.6 ± 18.3 mÅ (4.2σ) and at 21.410 Å with EW = 43.6 ± 29.4 mÅ (1.5σ). However, our attempts to detect another WA component using `pion` were unsuccessful, which may be due to the features being overwhelmed by noise in the spectrum.

Regarding the features at 24.305 and 21.410 Å as the O VII Heα and O VIII Lyα lines associated with the AGN, we derived similar outflow velocities of −287 km s^{-1} and −204 km s^{-1}, respectively. The derived magnitudes of outflow velocities fall outside the typical range observed for WA ($\lesssim 2000$ km s^{-1}, e.g., Laha et al. 2021). However, WAs with velocities between 2000 and 10,000 km s^{-1} have also been reported previously (e.g., 4000-6000 km s^{-1} in Mrk 335, Longinotti et al. 2013; approximately 5500 km s^{-1} in NGC 6814, Gallo et al. 2021). Therefore, an AGN origin of the two lines is still plausible.

Additionally, we have noticed that the typical EW of the O VII Heα line originating from intervening hot-gas structures is $\lesssim 15$ mÅ (e.g., Bregman et al. 2015; Nicastro et al. 2022). According to the prediction of the cosmological simulation by Cen & Ostriker (2006), the probability of detecting an intervening O VII absorber with an EW of 75 mÅ along an LOS with $z \sim 0.1545$ is $p \sim 3.5 \times 10^{-13}$ (see Bregman et al. 2015 for the details). This extremely low probability makes an intervening origin highly unlikely.

We also observed an edge-like absorption feature at around 17.5 Å (see Figure 2 [Figure 2: see original paper]). Modeling this feature in the RGS spectra with a Gaussian profile improved the fitting by ΔCstat/DoF = 20.1/3. The unresolved transition array (UTA) of Fe M-shell ions is known to produce edge-like absorption features at around 15-20 Å in the spectra of Seyfert galaxies (e.g., Sako et al. 2001). However, explaining this feature with UTA resulted in an unlikely outflow velocity of approximately $-30,000$ km s^{-1}. Overall, additional WA features are implied in the public RGS spectra of PG 0052+251, which may be resolved with future observations.

4.3. Potential Absorption from the Hot CGM in M31

Through the CIE model fitting, we obtained an LOS total hot gas absorption of $N_{\mathrm{H,total}} = (2.2 \pm 0.6) \times 10^{20}$ cm^{-2} at $z \sim 0$. To assess whether the hot CGM in M31 contributes to the observed absorption, we calculated the average MW contribution along the LOS of PG 0052+251 based on studies of the density profile of the Galactic hot halo. We selected the most recent and representative models (Li & Bregman 2017; Troitsky 2017; Kaaret et al. 2020; Martynenko 2022; Locatelli et al. 2024) obtained by analyzing all-sky data of the MW, with results reflecting the average properties of the Galactic hot halo. In addition to the hot halo, the models of Li & Bregman (2017), Kaaret et al. (2020), and Locatelli et al. (2024) contain a disk-shaped hot corona, which was also considered while calculating the MW contribution. Using the selected profiles, we integrated the hydrogen density from the observer to the virial radius to estimate the MW contribution of the hot-gas column density along the LOS. The derived hydrogen column density was later converted to the EWs of the hot CGM lines of interest using the curve-of-growth technique. Here, we adopted a Doppler-b parameter of 100 km s^{-1} for calculating the EW, which is the average Doppler-b value of the Galactic O VII absorption lines (e.g., Fang et al. 2015; Nicastro et al. 2016). We compare the LOS total hot-gas absorption, including hydrogen column density and EWs of the interested lines, with the derived MW foreground values in Table 4 .

Comparing the measurements toward PG 0052+251 with the estimated mean MW absorption reveals excess absorption of hydrogen column density and line EWs. The MW hydrogen column density derived by the selected density profiles ranges from $N_{\mathrm{H,MW}} = (0.63\text{-}1.33) \times 10^{20}$ cm^{-2}. The minimum and maximum expectations come from the models constrained by the XMM-Newton data (Li & Bregman 2017) and the eROSITA data (Locatelli et al. 2024), respectively. Subtracting the MW contribution from the total LOS column density of $(2.2 \pm 0.6) \times 10^{20}$ cm^{-2}, we obtain an excess column density of $N_{\mathrm{H,excess}} = (0.9\text{-}1.6) \times 10^{20}$ cm^{-2}. The significance level of this excess was estimated to be 2.2-2.6σ (Appendix), depending on the adopted MW profiles.

Qu et al. (2021) proposed a hot-gas bridge connecting the MW and M31 through their X-ray and tSZ analyses of the hot gas toward M31. Considering their fiducial SZ model of the bridge, it contributes to a hydrogen column density of approximately $N_{\mathrm{H,bridge}} = 0.34 \times 10^{20}$ cm^{-2} along the LOS of PG 0052+251. Note that this value has been adjusted using a metallicity of $0.3Z_{\odot}$ for comparison with our result. This column density is an order of magnitude smaller than the observed excess and is unlikely to fully account for it. However, the presence of the bridge will reduce the excess column density to $N_{\mathrm{H,excess}} = (0.6\text{–}1.3) \times 10^{20}$ cm^{-2}, with the significance level decreasing to 2.0–2.4σ. The LOS intersects the hot halo of M31 at an impact parameter of $R_{\mathrm{imp}} \sim 218$ kpc ($\sim 0.7R_{\mathrm{vir}}$). Considering the similarities between the MW and M31 and the fact that the amount of excess is consistent with the MW foreground contribution (both hydrogen column density and EWs of lines, see Table 4), the observed excess likely originates from the hot CGM in M31.

5. Summary

We analyze the public 73 ks XMM-Newton spectra of PG 0052+251, searching for absorption signals from the WA intrinsic to the target and the hot CGM of M31 at an impact parameter of 218 kpc. The absorption features are analyzed using either Gaussian profiles or plasma models. Both approaches reveal the presence of an intrinsic WA and the hot CGM at $z \sim 0$.

The identified WA in the RGS spectra has a column density of $N_{\mathrm{H}} = (1.0^{+1.1}_{-0.4}) \times 10^{20}$ cm^{-2} and an ionization parameter of $\log \xi = 0.17$. This WA component absorbs the spectral continuum at $\gtrsim 10$ Å and generates significant O II and O III absorption lines observed at 27.051 Å and 26.692 Å, respectively. Considering the consistent ionizing luminosity and ionization parameter, this is the same WA component previously discovered by Matzeu et al. (2023) in their analysis of the EPIC spectra. The high spectral resolution of RGS allows us to constrain the gas velocity. We find that this is a rarely observed inflowing WA component, with an inflow velocity of +156 km s^{-1}.

An excess absorption is revealed by comparing the LOS total hot-gas absorption at $z \sim 0$ with the MW foreground. The amount of the excess in hydrogen column density is estimated to be $N_{\mathrm{H,excess}} = (0.9\text{-}1.6) \times 10^{20}$ cm^{-2}, with a significance level of 2.2-2.6σ. This excess cannot be explained by the hot-gas bridge that connects the MW and M31 and is likely associated with the hot CGM in M31. Our analysis of PG 0052+251 suggests that the hot CGM in M31 could extend and remain detectable up to approximately $0.7R_{\mathrm{vir}}$.

Despite the identified WA and local hot gas, we have also observed two absorption lines at 24.305 Å and 21.410 Å, with EWs of 76.6 ± 18.3 mÅ and 43.6 ± 29.4 mÅ, respectively. The nature of the two lines remains unclear. However, based on the prediction of cosmological simulation by Cen & Ostriker (2006), the observed large EW makes an intervening scenario (e.g., hot halos and WHIM) unlikely but implies the presence of an additional WA component with $v_{\mathrm{out}} \sim -7000$ km s^{-1}. We also observed a deep absorption trough at $ $17.5 Å of unknown nature. These features are expected to be further clarified through deeper observations in the future.

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Appendix

Monte Carlo Simulations

We apply Monte Carlo simulations to estimate the statistical uncertainty of EW (see Luo et al. 2018 for further details) in our spectral fitting procedures. For the Gaussian line fitting, this simulation was run 1000 times for each analyzed absorption feature. Specifically, we generated simulated spectra for the 1–1.5 Å segment based on the best-fit model and the spectral data using the SPEX command `simulate`. These simulated spectra were later refitted using the same model. We recorded the EW value in each simulation, and the standard deviation of the simulated EW distribution was taken as the 1σ error range.

Using the same approach, we simulated 1–38 Å spectra of EPIC-pn and RGS based on the best-fit plasma model recorded in Table 3 . We generated and refitted the simulated spectra for 2000 times to derive the stochastic distributions of line EWs and LOS total N_{H} of the zero-redshift hot CGM. The EW uncertainties in Table 4 for the plasma model correspond to the standard deviations of these derived EW distributions. The purple histogram in Figure A1 [FIGURE:A1] displays the simulated distribution of the LOS total N_{H} for the zero-redshift hot CGM. We compare this distribution with the foreground contributions to estimate the probability (i.e., significance level) of observing the excess absorption, which likely originated from the hot CGM of M31.

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