Probing the Warm-Hot Circumgalactic Medium with broad O VI and X-rays

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ABSTRACT

Most of the baryonic mass in the circumgalactic medium (CGM) of a spiral galaxy is believed to be warm-hot, with temperature around $10^6$K. The narrow O VI absorption lines probe a somewhat cooler component at log T(K) = 5.5, but broad O VI absorbers have the potential to probe the hotter CGM. Here we present 376 ks Chandra LETG observations of a carefully selected galaxy in which the presence of broad O VI together with the non-detection of Ly$\alpha$ was indicative of warm-hot gas. The strongest line expected to be present at $\approx 10^6$K is O VII $\lambda$21.602. There is a hint of an absorption line at the redshifted wavelength, but the line is not detected with better than 2$\sigma$ significance. A physical model, taking into account strengths of several other lines, provides better constraints. Our best-fit absorber model has log T(K) = 6.3 $\pm$ 0.2 and log N$_{H}$(cm$^{-2}$) = 20.7$^{+0.3}_{-0.5}$. These parameters are consistent with the warm-hot plasma model based on UV observations; other O VI models of cooler gas phases are ruled out at better than 99% confidence. Thus we have suggestive, but not conclusive evidence for the broad O VI absorber probing the warm-hot gas from the shallow observations of this pilot program. About 800ks of XMM-Newton observations will detect the expected absorption lines of O VII and O VIII unequivocally. Future missions like XRISM, Arcus and Athena will revolutionize the CGM science.

1. Introduction

In recent years, the circumgalactic medium (CGM) of spiral galaxies has attracted a lot of scientific attention (see the review by [Tumlinson et al. (2017)]). The CGM is the gaseous medium surrounding the stellar disk of a galaxy, extended out to its virial radius (or perhaps twice the virial radius [Oppenheimer et al. 2016]). It serves as a gas reservoir with accretion from the intergalactic medium (IGM) and outflows from the stellar disk (star-formation and/or AGN induced). Some of this material may recycle back into the disk of the galaxy, while some may stay in the diffuse CGM. The CGM may help sustain and regulate star-formation and may harbor the largest baryon and metal reservoir of galaxies. As such, it is a very important

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component of a galaxy, but we are just about beginning to understand it. There have been significant theoretical developments in recent years (e.g. (Oppenheimer et al. [2016]), giving us insight into the physics of the CGM and also attesting to the importance of the CGM in the overall formation and evolution of galaxies.

The CGM is believed to be multi-phase, with most of its baryonic mass at temperatures of $10^5$–$10^7$ K, historically referred to as “warm-hot” (Cen & Ostriker [1999]). The cooler range of this, the warm CGM at $\approx 10^5$–$10^{5.5}$ K is probed by narrow UV absorption lines of Li-like metals; we will refer to this range as “warm” in the rest of the paper. The O VI absorption lines in the UV are among the best probes of the warm CGM ((Tumlinson et al. [2017]) and references therein).

At higher temperatures ($\approx 10^6$–$10^7$ K) metals become more highly ionized, He-like and H-like, observable only through X-ray absorption and emission lines; we will refer to this temperature range as “warm-hot” in the following sections. Because of our special vantage point, the warm-hot CGM has been best studied for our own galaxy, the Milky Way, both in X-ray absorption (Nicastro et al. [2002]; Wang et al. [2005]; Williams et al. [2005]; Fang et al. [2006]; Bregman & Lloyd-Davies [2007]; Gupta et al. [2012], 2014, 2017; Das et al. [2019c]) and emission ((Snowden et al. [2000]; Smith et al. [2007]; Galeazzi et al. [2007]; Henley et al. [2007]; Henley & Shelton [2008]; Gupta et al. [2009]; Das et al. [2019a]). X-ray observations of the CGM of external galaxies have had only limited success (e.g. Anderson et al. [2016] and references therein). Most of the observations were for massive galaxies; they were detected in X-ray emission, but the physical state, extent, temperature and density distribution profiles, and mass content of the CGM of these galaxies are poorly constrained. The only external L* galaxy in which the warm-hot CGM is detected in X-ray emission is NGC 3221 (Das et al. [2019b], 2020).

Blind searches of the warm-hot CGM of external galaxies with X-ray absorption spectroscopy are difficult for the lack of X-ray bright background quasars. Even with large exposure times, the resulting spectra have low signal-to-noise ratio (S/N), making it hard to assess the significance of the intervening absorption lines. With redshifts known a priori we can place higher confidence in the lines with lower detection thresholds, because we no longer have to pay the statistical penalty for searching a large number of resolution elements over the entire spectrum. This can be achieved by using “UV markers”; we can look for X-ray lines at redshifts defined by the UV absorption lines. Apart from the rare Ne VIII lines (Frank et al. [2018] and references therein), O VI are the highest ionization lines probing the warm gas, making them suitable anchors for X-ray searches. Moreover, oxygen is also one of the most abundant elements, making O VI absorbers promising probes of the warm gas. Even better anchors would be the broad O VI absorbers; in these systems the O VI lines are thermally broadened to $b > 25$ km s$^{-1}$ indicative of warm-hot gas at $T \geq 10^{5.7}$ K. The line broadening, however, could be because of non-thermal effects, such as turbulence, so not all broad O VI absorbers probe the warm-hot gas.

Savage et al. [2010] (hereafter SA10), Stocke et al. [2014] and Savage et al. [2014] (hereafter SA14) conducted a high S/N survey of 14 bright QSOs using HST/COS to discover warm ($10^{5.5}$ K) intervening absorbers. In the spectrum of PKS 0405-123, SA10 reported the discovery of a symmetric, broad O VI absorber ($b=52 \pm 2$ km s$^{-1}$) at $z \approx 0.167$. This is the first, and the only broad O VI intervening absorption system with no associated Ly$\alpha$, making this a unique laboratory for CGM studies. The line symmetry,
the $b$-value and the absence of associated Lyα absorption strongly suggest that it is produced in collisionally ionized warm-hot gas with $\log T(K) \approx 6.41$ and $\log N_{\text{H}}(\text{cm}^{-2}) \approx 20.5$ (SA10; SA14), and it likely originates in the CGM associated with a galaxy at $z=0.1668$. It is a luminous spiral $4.4L^*$ galaxy within $\Delta v < 100 \text{ km s}^{-1}$ of the absorber redshift and with an impact parameter of 116 kpc. SA10 do not rule out the possibility that the OVI absorption is produced in cooler gas with $\log T(K) = 5.8$ (see table [1] for all the possible solutions from SA10). The line broadening in that case could be because of non-thermal effects and the lack of Lyα may then be attributed to high oxygen abundance.

We observed this unique and interesting system with Chandra to look for the presence of the warm-hot gas from the CGM of the galaxy at $z=0.167$. The observations, data analysis, and spectral modeling are discussed in §2. We show that there is suggestive, but not conclusive evidence for the warm-hot gas in the CGM of the galaxy. In §3 we show that 800 ks of XMM-Newton observations will unequivocally detect the warm-hot gas, and Athena will require only 40 ks, opening a new window into the CGM science. Our conclusions are presented in §4.

2. Chandra Observations, Analysis, and Results

Our 385 ks observations of the background quasar PKS 0405-123 with Chandra LETG/HRC-S (PI: Gupta) took place in October and November of 2018. The actual exposure time was 376.36 ks and the effective LETG exposure time was 376.1 ks. We reprocessed the Chandra data with Chandra interactive analysis of observations (CIAO) software and extracted the grating spectra following the standard procedure in CIAO v4.10 [1]. Since HRC-S does not have clear order sorting, we included grating orders 1–6 in our analysis and combined the plus and minus orders. The spectrum showed practically no data beyond 3 keV, so we analyzed the spectrum in the 0.3–3 keV range. We binned the spectrum by four, to the LETG resolution; the count rate was found to be 0.1 counts/s. All the spectral analysis was performed with XSPEC v12.10.1 [2].

In all spectral models absorption by the Galactic column density of $N_{\text{H}}(\text{Gal}) = 3.54 \times 10^{20} \text{ cm}^{-2}$ [HI4PI Collaboration et al. 2016] was included and held fixed. The errors are quoted at 90% confidence, unless noted otherwise.

2.1. Model-independent analysis

We fitted the LETG spectrum with a power-law continuum and looked for the presence of the O VII absorption line at the redshift of the intervening galaxy. As noted above, the advantage of knowing the absorber redshift a priori is that we know the wavelength/energy of the expected lines; we therefore do not need to search for the lines over the entire spectrum. The strongest line expected from the warm-hot CGM is O VII $\lambda 21.602$; this gets redshifted to 25.21Å at $z = 0.167$. Therefore we looked for a line signature close

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1 https://cxc.harvard.edu/ciao/
2 https://heasarc.gsfc.nasa.gov/xanadu/xspec/
to this wavelength (at $E = 0.492$ keV). A line-like feature was present at the expected energy, so we added a Gaussian absorption line to the continuum model and fitted again. The line width was kept well below the instrumental resolution, to $\sigma = 0.1$ eV; thus the observed line width is due to the grating resolution. The best-fit parameters were as follows. The power-law $\Gamma = 1.94 \pm 0.04$ and normalization $= 6.9 \pm 0.1 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ and the line normalization $= -2.3 \pm 2.1 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ (90% confidence) (see figure 1).

The best-fit absorption line $\text{EW} = 1.1 \pm 0.6$ eV (1$\sigma$ error bars). The hard limit of normalization $= 0$ is reached at $\Delta \chi^2 = 3.26$, below the 2$\sigma$ confidence of $\Delta \chi^2 = 4$ (corresponding to 95.45% confidence). To evaluate the line detection significance further, we generated the $\chi^2$ contour of the line normalization, as shown in figure 1 right. The horizontal line marks the 2$\sigma$ confidence interval. Thus we see that the line is detected at just below 2$\sigma$ significance.

### 2.2. Modeling

In the above analysis, our focus was on the O VII line, which is expected to be the strongest at the warm-hot temperature. However, there is additional information in detection/non-detection of other H-like and He-like ions. Together, they can inform us about the temperature and column density of the CGM probed. With this in mind, we fitted the LETG spectrum with our hybrid photo- and collisional-ionization model hPHASE (Krongold et al. 2003). The free parameters of the model are plasma temperature $T$, column density $N_{\text{H}}$, and the (non-thermal) microturbulent velocity $v$. Since the warm-hot CGM is expected to be collisionally ionized, we kept the model photo-ionization parameter frozen to its lowest allowed value of $\log U = -4$, with negligible effect on the observed line ratios in the warm-hot plasma. The best-fit model parameters are $\log T(\text{K}) = 6.3 \pm 0.2$, $\log N_{\text{H}}(\text{cm}^{-2}) = 20.7^{+0.3}_{-0.5}$, and $v = 12^{+124}_{-12}$ km s$^{-1}$ (Table 1). The microturbulent velocity is not constrained, but shows that the lines are not resolved. On the other hand, the temperature and column density are very well constrained and the measured temperature is consistent with the observed $b$-value of the broad O VI absorption lines. This shows the power of model fitting using many lines of many ions. We note that the best-fit model O VII line $\text{EW} = 34.43$ mÅ is similar to the $\text{EW} = 41 \pm 22$ mÅ obtained by the Gaussian line fitting. In figure 2 we present the $\log T - \log N_{\text{H}}$ contour plot from the spectral fit. The “+” symbol refers to the best-fit values and the solid, dotted and dot-dash lines correspond to 68.3% (1$\sigma$), 90% (1.64$\sigma$), and 99% (2.58$\sigma$) confidence contours respectively. We see that the parameters are well-constrained at 68.3% and 90%, but not at 99%.

### 3. Discussion

Our hPHASE model contains more than 100 lines of multiple ionization states of ten elements (C, N, O, Ne, Mg, Si, S, Ar, Ca and Fe). Consistency of model predictions with data for all the lines provides a powerful tool to constrain the physical parameters of the absorbing warm-hot plasma. The upper limit on the temperature is driven by the O VIII line strength/weakness, and the lower limits by the strengths/weakness of
lower-ionization lines, even though the lines are not individually detected. The column density is constrained by the line strength at a given temperature. This is what we see with the good constraints on $T$ and $N_{\text{HI}}$ in the above analysis.

As noted in §1, SA10 argue that the broad O VI absorber in the spiral galaxy at $z = 0.167$ likely traces warm-hot gas. However, they could not rule out other models with cooler temperatures (SA10; their Table 5). We refer to their four models as S1, S2, S3, and S4; these are presented in table 1 and figure 2. We see that our best-fit model is closest with model S4 ($\log T(K) = 6.41$) and is consistent with S4 with 90% confidence. S1, S2, and S3 are ruled out at larger than 99% confidence. Once again, the consistency of the data on several lines with the model predictions allows for distinguishing among the models. For example, the best-fit model equivalent width of the O VIII Kα line is $\text{EW} = 19.68$ mÅ, similar to what is predicted by S4: $\text{EW} = 17.19$ mÅ. The predicted line EW for S1, however, is less than 1 mÅ. Similarly, the best-fit model predicted EW for the Ne IX $\lambda_{13.447}$ is $\text{EW} = 13.74$ mÅ, similar to $\text{EW} = 10.91$ for S4. But the line EW is predicted to be less than a mÅ for S1.

The above results, however, are model-dependent. In our models we have assumed that the warm-hot CGM is in collisional ionization equilibrium; while this is a reasonable assumption for an L* galaxy like the Milky Way, photoionization may play a non-negligible role in a 4L* galaxy that we probe here. However, as noted by SA10, for the photoionization model to be valid, the non-thermal microturbulent velocity needs to be associated with a symmetric flow to explain the symmetric line profile. It would have been nice to obtain model-independent results, but the weak detection of the O VII line makes the model distinction much more difficult based on the observed line strength. This can be seen in figure 3 where the black line is for the best-fit model and models S1, S2, S3 and S4 are shown by red, green, orange, and cyan lines respectively. We again see that the best-fit model is closest to S4, but S1, S2, and S3 cannot be ruled out at better than $2\sigma$. This shows that we should be cautious with the model-dependent results, but it also shows the power of model fitting. In figure 3 we also see that the model predictions for the O VII line are close for S2, S3 and S4, even though they correspond to quite different temperatures and column densities as shown in figure 2. Once again, this distinction comes because the model includes many lines of many elements.

### 3.1. The power of XMM-Newton and future missions

Given the low significance of the O VII line detection from our pilot observations with Chandra, it is vital to obtain model-independent results with high S/N spectra in which individual lines are detected unambiguously. With this goal, we simulated XMM-Newton RGS spectra assuming the best-fit parameters from the Chandra data. In addition to detecting the O VII $K\alpha$ line with confidence, it would be important to detect the O VIII $K\alpha$ line; the O VII to O VIII ratio would determine the gas temperature in a model-independent way. To detect the O VIII line at $\geq 3\sigma$, 815 ks of XMM-Newton time would be necessary. With this exposure time the O VII $K\alpha$ line would be detected at $\geq 7\sigma$ (figure 4). To detect the O VII $K\beta$ line at $\approx 3\sigma$ would require more than double this time of 1.75Ms.

Future JAXA/NASA mission XRISM will have a soft X-ray spectrometer with 5–7 eV resolution.
calorimeters. XRISM is expected to launch in 2021. Arcus is a high resolution X-ray grating spectrometer mission that was proposed to NASA as a medium class mission and it is selected for a Phase A concept study. The combination of high resolution and high effective area of these missions will open a new window on the CGM science.

Athena is the planned large X-ray astronomy mission of the European Space Agency, scheduled to launch in 2031; it is being designed to study the “hot and energetic Universe.” The X-ray Integral Field Unit (XIFU) on board Athena has high spectral resolution and large area, making it well-suited for the studies of the warm-hot intergalactic and circumgalactic medium. We simulated Athena XIFU spectra of the PKS 0405-123 sightline assuming the best-fit parameters from the Chandra observations. With just 38ks of Athena observations, we will detect the O\textsuperscript{VII} $K\alpha$ line at $>10\sigma$ and the O\textsuperscript{VIII} line at $>5\sigma$ (figure 4). The O\textsuperscript{VII} $K\beta$ line will also be detected at $5\sigma$. The O\textsuperscript{VII} $K\alpha$ to $K\beta$ ratio is informative of line saturation, allowing precise determination of the column density and the velocity dispersion parameter in a model-independent way. We can constrain the nonthermal microturbulent velocity down to $20$ km s$^{-1}$ at a $3\sigma$ level. Thus the CGM science will be revolutionized with Athena.

4. Conclusion

We present 376 ks Chandra LETG observations of a carefully selected galaxy in which the presence of broad O\textsuperscript{VI} together with the non-detection of Ly$\alpha$ was indicative of warm-hot gas. Our best-fit absorber model has $\log(T/K) = 6.3 \pm 0.2$ and $\log(N_{H}/cm^{-2}) = 20.7^{+0.3}_{-0.5}$. This is consistent with the warm-hot plasma model (S4) based on UV observations of SA10. The cooler models of SA10 (S1, S2, and S3) are ruled out at 99% confidence. However, the strongest absorption line of O\textsuperscript{VII} is barely detected below $2\sigma$ significance in the Chandra spectrum. Thus we have a suggestive, but not conclusive evidence for broad O\textsuperscript{VI} absorber probing warm-hot gas from the shallow observations of this pilot program. 811 ks XMM-Newton observations will clearly detect O\textsuperscript{VII} and O\textsuperscript{VIII} lines, allowing us to determine the physical conditions in the CGM in a model-independent way. With just 38ks of Athena time, we will additionally detect the O\textsuperscript{VII} $K\beta$ line, opening a new window into the CGM science.

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\footnote{https://sci.esa.int/web/athena/home}
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Facilities: Chandra, XMM-Newton.
Software: CIAO (Fruscione et al. 2006), HeaSoft v6.17 (Drake 2005), DS9 (Joye & Mandel 2003)
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Table 1: Best fit *Chandra* model and the UV models

| Model          | \(\log T\) K | \(\log N_H\) cm\(^{-2}\) | \(v\) km s\(^{-1}\) | Photon Index \(\Gamma\) | Normalization \(10^{-4}\) | \(\chi^2\) (738 dof) |
|----------------|--------------|------------------|----------------|----------------|----------------|------------------|
| X-ray Best-fit: Continuum |              |                  |                |                |                |                  |
| hPHASE         | 6.3 ± 0.2    | 20.7\(^{+0.3}_{-0.5}\) | 12\(^{+1.25}_{-1.2}\) | 1.97 ± 0.04 | 6.9 ± 0.1 | 588.28           |
| UV models:     |              |                  |                |                |                |                  |
| S1             | 5.8          | 19.11            | 45.3           |                |                | 603.10           |
| S2             | 6.0          | 19.71            | 40.8           |                |                | 600.54           |
| S3             | 6.11         | 19.87            | 36.8           |                |                | 598.95           |
| S4             | 6.41         | 20.50            | 0              |                |                | 591.39           |

The power-law normalization is in the units of photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\).

The UV models are from SA10.
Fig. 1.— Left: *Chandra* LETG spectrum fitted with an absorbed power-law continuum and a Gaussian absorption line at 0.492 keV (25.21 Å; O\textsc{VII} λ21.602 at z=0.167). Right: The χ² curve of the Gaussian line normalization (in the units of photons cm⁻² s⁻¹ keV⁻¹). The solid horizontal line is for the best-fit χ² = 592.67 and the dashed horizontal line shows Δχ² = 4 corresponding to the 2σ significance. Thus the line is detected at just below 2σ significance.

Fig. 2.— The contour plot showing the temperature–column density plane. The “+” denotes the best-fit values, and the sold, dotted and dot-dash lines correspond to 68.3%, 90%, and 99% confidence contours respectively. S1, S2, S3, and S4 refer to the four model parameters in Savage et al. 2010. The best-fit model is consistent with S4, and S1, S2, S3 are ruled out at better than 99% confidence.
Fig. 3.— The spectrum around the O\textsc{vii} line with best-fit (black), S1(dot-dashed red), S2 (dashed green), S3 (solid orange) and S4 (dashed cyan) models. The S4 model is closest to the data and the best-fit model. The S1, S2 and S3 models are close to each other and the O\textsc{vii} line strength is also consistent with them.
Fig. 4.— The simulated 815 ks XMM-Newton spectra (top) and 38 ks Athena spectra (bottom), assuming the best-fitted Chandra model. XMM-Newton RGS1, RGS2 and Athena IFU spectra and the models are shown with green, blue and red points and curves respectively. The right panels show the redshifted O\textsc{vii} K\textalpha line. The line would be detectable at \( \geq 6\sigma \) with XMM-Newton and at \( \geq 10\sigma \) with Athena. The left panels show the redshifted O\textsc{viii} K\textalpha and O\textsc{vii} K\textbeta lines. The O\textsc{viii} K\textalpha would be detectable at \( \geq 3\sigma \) with XMM-Newton. O\textsc{viii} K\textalpha and O\textsc{vii} K\textbeta would be detectable at \( > 5\sigma \) and \( > 3\sigma \) with Athena. The vertical dashed line is the location of the \( z = 0 \) O\textsc{vii} K\textalpha line, which is not detected in the Chandra spectrum.