The Hot Circumgalactic Medium of the Milky Way: Evidence for Supervirial, Virial, and Subvirial Temperatures; Nonsolar Chemical Composition; and Nonthermal Line Broadening

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Abstract

For the first time, we present the simultaneous detection and characterization of three distinct phases at $>10^5$ K in $z=0$ absorption using deep Chandra observations toward Mrk 421. The extraordinarily high signal-to-noise ratio ($\geq 60$) of the spectra has allowed us to detect a hot phase of the Milky Way circumgalactic medium (CGM) at $3.2^{+1.5}_{-0.3} \times 10^6$ K coexisting with a warm-hot phase at $1.5 \pm 0.1 \times 10^6$ K and a warm phase at $3.0 \pm 0.4 \times 10^6$ K. The warm-hot phase is at the virial temperature of the Galaxy, and the warm phase may have cooled from the warm-hot phase, but the supervirial hot phase remains a mystery. We find that [C/O] in the warm and warm-hot phases, [Mg/O] in the warm-hot phase, and [Ne/O] in the hot phase are supersolar, and the hot and the warm-hot phases are $\alpha$-enhanced. Nonthermal line broadening is evident in the warm-hot and the hot phases, and it dominates the total line broadening. Our results indicate that the $>10^5$ K CGM is a complex ecosystem. It provides insights on the thermal and chemical history of the Milky Way CGM and theories of galaxy evolution.

Unified Astronomy Thesaurus concepts: Circumgalactic medium (1879); Quasar absorption line spectroscopy (1317); Galaxy evolution (594); Galaxy chemical evolution (580); X-ray astronomy (1810); Galaxy formation (595); Milky Way formation (1053); Milky Way Galaxy (1054); Milky Way evolution (1052); Milky Way Galaxy physics (1056); Hot ionized medium (752); Interstellar absorption (831)

1. Introduction

The circumgalactic medium (CGM) is the halo of multiphase gas and dust surrounding the stellar component and interstellar medium (ISM) of galaxies extending out to their virial radii (Tumlinson et al. 2017). It plays an instrumental role in the evolution of a galaxy as a nexus of accretion, feedback, and recycling (Putman et al. 2012; Schaye et al. 2015; Voit et al. 2015; Nelson et al. 2018) by harboring a large fraction of its missing baryons and missing metals (Gupta et al. 2012; Peeples et al. 2014). The temperature of the CGM is predicted to span at least two orders of magnitude: $T \approx 10^4$–$10^5$ K, but most of its mass is believed to reside in the volume-filling warm-hot ($T \approx 10^6$ K) component (Oppenheimer et al. 2016; Li et al. 2017; Nelson et al. 2018).

The warm-hot gaseous Galactic corona at the virial temperature has been predicted for a long time (Spitzer 1956). For $\geq 10^{12} M_\odot$ halos, the warm-hot CGM is expected to be an amalgam of the rarefied, metal-poor, shock-heated inflowing gas that has not yet cooled and fallen to the disk and the dense metal-enriched galactic outflow driven by the winds of massive stars, supernovae, and active galactic nucleus feedback. Therefore, the warm-hot CGM is not necessarily a phase at a single temperature and of solar-like chemical composition. Studying the abundances in the highly ionized CGM and its different thermal components, if any, is extremely important to understand the thermal and chemical evolution of the CGM and any contribution from the sources of nonthermal energy. Deep X-ray absorption spectroscopy, where the warm-hot CGM can be probed by He-like and H-like ionized metals, provides a great tool.

Because of our special vantage point, the warm-hot CGM of the Milky Way (MW) has been studied via emission and absorption in much better detail compared to other galaxies. The combined studies of emission and absorption show that the warm-hot CGM is at $T \approx 10^{6.3}$ K, and it is diffuse, extended, massive, and anisotropic (Kuntz & Snowden 2000; Gupta et al. 2009, 2012, 2014, 2017; Henley et al. 2010; Henley & Shelton 2013; Nicastro et al. 2016b; Gatzu & Churazov 2018). From both the emission and absorption studies focused on O VII and O VIII lines, the warm-hot CGM was found to be consistent with a single temperature. There were hints of hotter components in some emission studies, but these were questionable due to confusion with the foreground components (Yoshino et al. 2009; Henley & Shelton 2013; Nakashima et al. 2018).

By analyzing a deep spectrum toward the blazar 1ES 1553+113 observed with the XMM-Newton Reflection Grating Spectrometer (exposure time $= 1.85$ Ms), Das et al. (2019b) discovered a $\approx 10^7$ K CGM component coexisting with the $\approx 10^6$ K component. The discovery of the $\approx 10^7$ K hot component, driven by the detection of the Ne X line, was unambiguous and robust. The emission analysis around the same sight line revealed that the temperatures of the emitting and the absorbing gas were not the same (Das et al. 2019a), unlike the previous studies of a one-temperature emitting model (Gupta et al. 2012, 2014, 2017). This showed that the highly ionized halo gas consists of at least three components, and the picture of an

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5 The circumgalactic gas of the Milky Way is usually referred to as the Galactic “halo” or “corona.” CGM is a more prevalent term for external galaxies. Because they all mean essentially the same, we will use these terms interchangeably.

6 Traditionally, “warm-hot” refers to the temperature range of $T = 10^5$–$10^7$ K (Cen & Ostriker 1999). In this paper, we refer to the $10^5$–$10^7$ K range as warm-hot and the $10^5$–$10^6$ K range as warm.
isothermal CGM at the virial temperature is clearly ruled out. Evidence of hotter CGM component(s) has further been supported by emission analysis toward other sight lines (Gupta et al. 2021).

The discovery of the ≈10^7 K gas at supravirial temperature in the MW CGM was surprising and perplexing. How ubiquitous is the ≈10^7 K hot gas? Detecting the weak lines probing the hot component requires exceedingly high signal-to-noise ratio (S/N) spectra. In this paper, we present analysis of the z = 0 absorbers toward the blazar Mrk 421 using the archival Chandra data. The sight line probes the MW CGM in absorption with unprecedented sensitivity. Detailed spectral analysis and ionization modeling of the data have led to the discovery of a very hot component of the MW CGM at T_3 ≈ 10^7.5 K, coexisting with two phases at T_1 ≈ 10^5.5 K and T_2 ≈ 10^5.2 K. Nonthermal broadening is found to dominate the total line broadening in the two hotter phases. We also find that the phases at T_2 and T_3 are α-enhanced, indicating core-collapse supernova enrichement. Additionally, we find nonsolar abundance ratios of α-elements (C, O, Ne, Mg, and Si).

Our paper is structured as follows. We discuss data reduction and analysis in Section 2 and results in Section 3. We interpret our results and discuss their implications in Section 4. Finally, we summarize our results and outline the future aim in Section 5.

2. Data Reduction and Analysis

Mrk 421 (l, b = 179°83, 65°03) is one of the nearby (z = 0.031) brightest blazars in the sky. For the past 20 yr, it has been observed by multiple detectors and gratings of Chandra both as a target of opportunity (ToO) and as a calibration source. Here, we focus on the z = 0 absorption lines of multiple metals in the 4.9–43.4 Å range of the spectra, probing the CGM of the MW. We use the optimum combination of the detectors and gratings according to their effective area and spectral resolution. With the medium-energy grating (MEG) arm of the high-energy transmission grating (HETG) of ACIS-S, we probe the magnesium (Mg) and silicon (Si) lines. With the low-energy transmission grating (LETG) of ACIS-S, we probe neon (Ne) and oxygen (O) lines. And with HRC-S/LETG, we probe nitrogen (N) and carbon (C) lines. Thus, the three-instrument setting together allows us to probe the large wavelength range we report here, which is critical to search for multiple temperature components.

We use χ^2 (XSPEC command chi) statistic throughout our analysis. In the following sections, we quote 1σ error bars and 68% confidence intervals, unless explicitly mentioned otherwise.

2.1. Data Extraction and Reduction

From the public archive of Chandra we extract all the archival data of ACIS-MEG and HRC-LETG. The effective area of ACIS-LETG degraded significantly after cycle 15, therefore we use the data only after then.

We reprocess and reduce all the data using the latest calibration database of CIAO 4.13 with the chandra_repro command. It produces the spectra, background spectra, response matrices (RMF), and auxiliary response files (ARF) for each observation ID. We combine the positive and negative first-order spectra of all observation IDs separately for ACIS-MEG, ACIS-LETG, and HRC-LETG using the combine_grating_spectra command. In HRC-LETG, the diffraction orders of the spectra cannot be resolved, so the spectrum is a combination of all orders. To account for the contribution of higher orders in the spectra, we combine the second- to eighth-order positive and negative RMFs and ARFs, separately for each order, of each observation ID using the add_resp command. In addition to the first-order RMF and ARF, we load the higher-order responses to the HRC-LETG spectrum while doing the spectral analysis in XSPEC.

The total exposure time of ACIS-MEG, ACIS-LETG, and HRC-LETG data are 283.5 ks, 627.8 ks, and 604.7 ks, respectively. This yields X-ray grating spectra with S/N per resolution element (SNRe)^10 of 59, 87, and 62, presented in Figure 1. Strong lines of highly ionized metals at z = 0 are clearly seen at the expected wavelengths (Table 1).

2.2. z = 0 Lines: Ionization-model-independent Results

The first step to detecting and characterizing the absorption lines is to determine the source continuum. The continuum of Mrk 421 has varied remarkably over 20 yr, both in shape and normalization. Fitting a global continuum over a large range of wavelengths is notoriously challenging, therefore we fit the portions of the continuum spectra in ACIS-MEG (5–10 Å), ACIS-LETG (10–24 Å), and HRC-LETG (24–43 Å) separately. We discuss the continuum modeling in detail in Appendix A. Our focus here is the absorption lines of He-like and H-like metal ions, not the details of the continuum shape; they do not affect our analysis.

After fitting the continuum and other line-like residuals, we model the transitions of He-like and H-like ions of C, N, O, Ne, Mg, and Si with unresolved absorbing Gaussian profiles (agauss). We allow the central wavelengths to vary within the resolution element around their theoretical z = 0 values.

We detect the absorption lines of C V Kα (6.4°), Kβ(4.2°), and Kγ (2.7°); C VI Kα (6.0°); N VI Kα (3.0°); O VII Kα (18.1°) and Kβ (6.5°); O VIII Kα (5.0°); Ne IX Kα (4.7°); Ne X Kα (3.2°); and Mg XI Kα (4.2°) and Si XIV Kα (3.6°) (Figure 1). We also provide 3σ upper limits on N VII Kα, N VII Kα, Mg XII Kα, and Si XIII Kα.11 We list the equivalent widths (EWs) in Table 1.

While estimating the continuum, we took a conservative approach and did not mask the wavelengths around the He-like and H-like metal ions. To test if this biases our results, we refit the continuum by removing the ±0.1 Å region around each ion. Then we add these wavelength regions back and recalculate the EWs. From carbon to silicon, the best-fitted EWs of the ions detected with >2σ are 6.66, 4.13, 2.06, 5.80, 3.03, 14.65, 3.88, 3.03, 1.65, 1.15, 1.26, and 1.12 mA, respectively. These are consistent with the previously obtained best-fitted values within 1σ (see Table 1). The upper limits of Mg XII and Si XIII are

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10 The resolution element is defined as the half-width half maximum (HWHM) of the line spread function (LSF), which is 12.5 mA and 25 mA for MEG and LETG, respectively.
11 We define the single-line statistical significance as EW/σ(EW), where DEW is the 1σ error of EW in the negative side.
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similarly consistent as well. The evidence for NVI K
Figure 1.
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absorbers modeled with Gaussian lines is shown. The residuals are plotted in
increases to 2.0
N VII K
respectively
1.14 mÅ
0 emission feature.
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lines becomes stronger as the detection signi
Each subplot shows the data, i.e., the spectra folded with the effective
and the unfolded spectra
150. The best-
and the ionization fraction of H-like ions
which we discuss below.
In collisional ionization equilibrium (CIE), the ionization fraction of He-like ions (e.g., O VII) plateau at a high value
(>0.8) across a definite range of temperatures. Similarly, the ionization fraction of H-like ions (e.g., O VIII) peaks at
definite temperatures. Therefore, the column density ratio of the same element’s two ions can uniquely determine the
temperature (T_ratio), assuming the ions are exclusively coming from a single phase. We estimate the temperature (or its limit)
for each element individually.
The C V to C VI ratio implies T = 7.1 ± 0.4 × 10^5 K; the N VI to N VII ratio implies T = 1.1 ± 0.2 × 10^6 K; the O VII to
O VIII ratio implies T = 1.5 ± 0.1 × 10^6 K; the Ne IX to Ne X ratio implies T = 3.1 ± 0.4 × 10^6 K; the Mg XI to
Mg XII ratio implies T < 7 × 10^6 K; and the Si XIII to Si XIV ratio implies T = 2.8^{+1.0}_{-0.8} × 10^7 K. Clearly, the temper-
ature windows do not overlap with each other. This suggests that a single-,
or even two-temperature, model may be
inadequate to characterize the observed spectra.
Additionally, the column density ratio of two elements provides an approximate abundance ratio of those elements.
This is valid under the assumption that both the elements are
from the same phase and are copatial. We calculate the column density of an element using the measured column
density of the ion with higher signi
for each element individually.
Given the solar abundance ratios from Asplund et al. (2009), we find that [N/O] = 1.1 ± 0.3 N/O⊙,[Ne/O] = 1.5^{+0.8}_{-0.6}Ne/O⊙,
and Mg/O ≥ 1.8^{+0.7}_{-0.6} Mg/O⊙. This suggests that nitrogen is in
decrease systematically due to masking the surrounding
wavelengths. This shows that the estimation of EWs and the quantities derived from it are not affected by the approach of
continuum fitting (see Appendix A) for details.
We calculate the column densities (or the upper limits for the undetected ones) of the ions from their respective EWs
assuming that they lie on the linear regime of the curve of growth (Table 1). We also estimate the column densities of C V, N VI, and O VII by combining the information on their Ka and Kaβ lines, as has been done previously by Williams et al.
(2005), Gupta et al. (2012, 2017), Nicastro et al. (2016a), N(C V), N(N VI), and N(O VII) calculated this way are larger than those calculated in the curve-of-growth analysis (Table 1), indicating that their Ka lines are likely saturated.
The absorption lines we detect, or obtain an upper limit on,
suggest several interesting aspects of the observed system in
terms of the temperature and the abundance ratios of metals,
which we discuss below.
The b-parameters of C V and N VI are similar: b_C = 15 ±
3 km s^{-1}, b_N = 11 ± 3 km s^{-1}, but they are different from the
b-parameter of O VII: b_O = 73 ± 5 km s^{-1}. Assuming the
velocity broadening to be purely thermal, it corresponds to
the temperature of T_C = 1.7 ± 0.6 × 10^5 K, T_N = 1.0 ± 0.6 ×
10^5 K, and T_O = 5.1 ± 0.7 × 10^6 K. This suggests that the
detected carbon, nitrogen, and oxygen lines are not coming
from the same phase; there are either multiple temperature
components and/or nonthermal line broadening.
Figure 1. Each subplot shows the data, i.e., the spectra folded with the effective
area and LSF (top) and the unfolded spectra (middle) of Mrk 421, in bins with
an S/N per bin ≥ 150. The best-fit continuum (Section 2.2) with z = 0
absorbers modeled with Gaussian lines is shown. The residuals are plotted in
the bottom panels. The location of the Si XIII absorption line is on top of a
broad Gaussian continuum feature (see Section 2.2); it is not identified as a
z = 0 emission feature.
similarly consistent as well. The evidence for N VI Kβ and
N VII Ka lines becomes stronger as the detection significance increases to 2.0σ due to the new, larger best-fit EWs (from
1.14 mA to 1.29 mA, and from 1.10 mA to 1.26 mA,
respectively). The best-fit EWs of all ions do not increase or
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Table 1

Absorption-line Parameters with 1σ Errors

| Ion   | Transition | $\lambda$ (Å) | EW (mA) | $N_{H}$ (cm$^{-2}$) | $N_{Si}$ (cm$^{-2}$) | $N_{Fe}$ (×10$^{15}$ cm$^{-2}$) | $N_{Fe}$ (×10$^{15}$ cm$^{-2}$) |
|-------|------------|---------------|---------|---------------------|----------------------|----------------------------------|----------------------------------|
|       |            | (Å)           | (mA)    | (cm$^{-2}$)         | (cm$^{-2}$)          | (×10$^{15}$ cm$^{-2}$)            | (×10$^{15}$ cm$^{-2}$)            |
| CV    |            |               |         |                     |                      |                                  |                                  |
| Kα    | 1.6        | 2.3 ± 0.2     | ...     | 1.87 ± 0.02         |                      |                                  |                                  |
| Kβ    | 3.98       | 2.3 ± 0.2     | ...     | 0.78 ± 0.12         |                      |                                  |                                  |
| Kγ    | 4.76       | 2.3 ± 0.2     | ...     | 2.74 ± 0.52         |                      |                                  |                                  |
| C VI  |            |               |         |                     |                      |                                  |                                  |
| Kα    | 5.98 ± 0.78| 1.0 ± 0.2     | 1.0 ± 1.0 | 2.0 ± 0.6 | 1.50 ± 0.14 | 1.4 ± 0.17                     |                                  |
| Kβ    | 6.08 ± 0.78| 1.0 ± 0.2     | 1.0 ± 1.0 | 2.0 ± 0.6 | 1.50 ± 0.14 | 1.4 ± 0.17                     |                                  |
| O VIII|            |               |         |                     |                      |                                  |                                  |
| Kα    | 7.48       | 2.3 ± 0.2     | ...     | 0.78 ± 0.12         |                      |                                  |                                  |
| Kβ    | 8.08       | 2.3 ± 0.2     | ...     | 2.74 ± 0.52         |                      |                                  |                                  |
| Ne IX |            |               |         |                     |                      |                                  |                                  |
| Kα    | 12.13      | 2.3 ± 0.2     | ...     | 1.0 ± 0.2           |                      |                                  |                                  |
| Kβ    | 12.13      | 2.3 ± 0.2     | ...     | 1.0 ± 0.2           |                      |                                  |                                  |
| Mg XI |            |               |         |                     |                      |                                  |                                  |
| Kα    | 21.60      | 2.3 ± 0.2     | ...     | 0.78 ± 0.12         |                      |                                  |                                  |
| Kβ    | 21.60      | 2.3 ± 0.2     | ...     | 2.74 ± 0.52         |                      |                                  |                                  |
| Si XIV|            |               |         |                     |                      |                                  |                                  |
| Kα    | 24.78      | 2.3 ± 0.2     | ...     | 0.78 ± 0.12         |                      |                                  |                                  |
| Kβ    | 24.78      | 2.3 ± 0.2     | ...     | 2.74 ± 0.52         |                      |                                  |                                  |
| Notes. For lines with <2σ significance, we quote 3σ upper limits. The eighth column is the summation of the fifth to seventh columns, which are the results of PHASE modeling. The equivalent widths and corresponding column densities obtained from Gaussian line fitting are in the fourth and the ninth column, respectively. The column densities of the α and β transitions of CV, NV, and OVII from Gaussian line fitting have been shown separately in the ninth column. The absorption by CV, NV, and OVII have multiple temperature components of different strengths. Therefore, the column density obtained by combining the Kα and Kβ transitions of the same ion is not applicable; these are shown as numbers with a line through them. b By simultaneously fitting ACIS-MEG, ACIS-LETG, and HRC-LETG, the EW = 0.63 ± 0.19 ± 0.14 mA and N = 1.14 ± 0.34 ± 0.26 × 10$^{15}$ cm$^{-2}$. By simultaneously fitting ACIS-LETG and HEG, the EW = 0.90 ± 0.26 ± 0.01 mA and N = 1.64 ± 0.46 ± 0.01 × 10$^{15}$ cm$^{-2}$. The first error bars are average statistical uncertainties and the second error bars are systematic uncertainties due to multiple gratings/instruments.

2.3. PHASE Modeling of the z = 0 Absorbers

To confirm and to quantitatively determine the suggestive results obtained in Section 2.2, we now model the data in detail. We use the hybrid-ionization model PHASE (models of collisionally ionized gas perturbed by photoionization by the meta-galactic radiation field, at a given redshift; Krongold et al. 2003; Nicastro et al. 2018; Das et al. 2019b) to fit the data. The free parameters of the PHASE model are the temperature T, equivalent hydrogen column density $N(H)$, the relative abundance of the metals in the absorbers, nonthermal line broadening $b_{NT}$, photoionization parameter U, and redshift z (equivalent to line-of-sight velocity). The model assumes relative abundances and absolute metallicities to be solar by default, but allows them to vary between 0.01 and 100 times solar, independently for each element: He, C, N, O, Ne, Mg, Al, Si, S, Ar, Ca, Fe, and Ni.

In our models, we allow T, $N(H)$, $b_{NT}$, and the relative abundance of the metals to vary. C, N, O, Ne, Mg, and Si have prominent absorption features (Figure 1), and Fe lines e.g., Fe XIX (13.425 Å), Fe XVII (12.123 Å), Fe XXI (12.165 Å), and Fe XXII (9.163 Å and 9.183 Å) can contaminate the Ne IX, Ne X, and Mg X lines through blending. Therefore, we vary the abundances of C, N, Ne, Mg, Si, and Fe with respect to O. The spectrum is insensitive to the abundances of other elements, so we freeze their abundances with respect to oxygen at solar. The CGM is assumed to be in CIE, therefore we freeze U to the lowest possible value allowed by PHASE, at U = 10$^{-4}$, ensuring that photoionization is negligible. The best-fit central wavelengths of the absorbers are consistent with their theoretical values within spectral resolution, indicating no significant line-of-sight velocity. Therefore, we keep z frozen at 0.

To begin with, we fit the whole spectrum with a single-temperature PHASE model with solar composition. The best-fit model ($\chi^2$/dof = 3757.93/3625) is a significant improvement over the continuum ($\chi^2$/dof = 4275.16/3628), as is expected from the existence of the absorption lines. This model severely underestimates the Mg XI line although it is expected to be present at the best-fit temperature. This indicates that either the abundance ratios are nonsolar and/or another temperature component is needed. Therefore, we fit the spectra with a two-temperature model and solar composition. This model provides a better fit ($\chi^2$/dof = 3747.64/3622) than the single-temperature solar composition model, showing that multiple temperatures are necessary. Next, we fit the spectra with a single-temperature model and solar composition.

12 $U$ is the flux of ionizing photons per unit density of gas: $U = \frac{Q(H)}{4\pi d^2 \rho}$, where $Q(H)$ is the number of hydrogen ionizing photons s$^{-1}$, r is the distance to the source, and $\rho$ is the number density of hydrogen.

13 ACIS-LETG (5–10 Å), ACIS-LETG (10–24 Å), and HRC-LETG (24–43 Å) simultaneously.
temperature model, but with nonsolar composition (PHASE_A). This also improves the fit ($\chi^2$/dof = 3735.28/3620), but it cannot reproduce all of the detected lines in the spectra; in particular, it does not account for the C V, Ne X, and Si XIV lines.

To see if the nonsolar abundance ratios are necessary in the multiple temperature scenario, we fit the spectra with two PHASE models (PHASE_A+PHASE_B). We allow the H column density and the temperatures in two phases to be different but do not force them to be different. Most of the metal ions of interest probe only one of the two temperatures (e.g., carbon and nitrogen probe the lower temperature while silicon probes the higher temperature), therefore we force the relative abundances of light elements ([C/O], [N/O], and [Si/O]) to be the same in both phases. Ne, Mg, and Fe, on the other hand, have lines in both temperature components (see Section 2.2), so we allow [Ne/O], [Mg/O], and [O/Fe] to be different in the two phases. The two-temperature nonsolar composition model provides a better fit ($\chi^2$/dof = 3707.30/3614) than the two-temperature solar composition model, and it accounts for the Ne X and Si XIV lines.

The two-temperature nonsolar composition model cannot reproduce the C V lines, and it underestimates the N VI line. This is not unexpected; the $b$-parameters of C V and N VI indicated a lower temperature than that indicated by all other ions (see Section 2.2). Therefore, we further add another PHASE component (PHASE_C). We do not force the temperature and the H column density of this phase to be different from the other two phases. We allow [C/O] to be different from the other phases because C V can independently constrain this temperature. There are no detectable Ne, Mg, and Fe lines in the expected temperature range of the third component, so we assume the [Ne/O], [Mg/O], and [O/Fe] ratios to be solar in this phase. The nitrogen lines are too weak to independently constrain the two temperatures (one dominated by N VII and the other by N VI), so we tie the [N/O] of this phase to be the same as the first phase.

The three-temperature nonsolar composition model (PHASE_A+PHASE_B+PHASE_C) fits the data better ($\chi^2$/dof = 3673.58/3610) than the previous models, reproduces all the detected lines, and is consistent with the nondetections. This is our final spectral fit. The best-fit parameter values in PHASE models are quoted in Table 2.

We have allowed the nonthermal broadening of metal lines $b_{nt}$ to vary throughout our analysis. To test if the nonthermal components are really necessary, we refit the spectrum with $b_{nt}$ in all phases forced to be zero and find that the best-fit model becomes worse: $\chi^2$/dof = 3698.50/3613. This confirms that nonthermal broadening is required to fit the spectrum.\(^{14}\)

The spectral resolution corresponds to a velocity resolution $\Delta v$ of $\approx 250$ km s$^{-1}$ around the N VI and C V lines (tracers of PHASE_C at $T_3$), $\Delta v$ of 220, 350, 560, and 410 km s$^{-1}$ around C VI, O VII, Ne IX, and Mg XI lines (tracers of PHASE_A at $T_2$), respectively, and $\approx 610$ km s$^{-1}$ around the Si XIV and Ne X lines (tracers of PHASE_B at $T_3$). The thermal broadening $b_T$ calculated from the best-fit temperatures (Table 2) are 18–20 km s$^{-1}$, 32–46 km s$^{-1}$, and 128–221 km s$^{-1}$ for $T_1$, $T_2$, and $T_3$ respectively. By comparing the broadening of the lines $\sqrt{(b_T^2 + b_{nt}^2)}$ in each phase with $\Delta v$, we can see that most of the ions are not resolvable (Figure 2). Ne X and Si XIV should be partially resolvable at the best-fit value of $b_{nt}$, but the large error on $b_{nt}$ pushes it to the limit of not being resolvable. This is consistent with our model-independent results where we assume the lines to be unresolved (Section 2.2).

The nonthermal broadening of a line may be the manifestation of more than one thermally broadened line, with the central wavelengths shifted due to a nonzero line-of-sight velocity. The velocity resolution of the spectrum does not allow us to distinguish between the two cases of nonthermal broadening versus multiple velocity components. This is consistent with the model-independent results (Section 2.2) where the observed wavelength of the lines did not indicate any line-of-sight velocity larger than the velocity resolution.

The column densities of the detected ions from the three-temperature PHASE model are presented in Table 1 (fifth to seventh columns). The sum of these column densities is given in the eighth column. Comparing these with the column densities estimated from the curve-of-growth analysis (ninth column), we find that the two are consistent with each other within 2$\sigma$.

\(^{14}\) $\Delta \chi^2$ after forcing $b_{nt}$ to be zero in PHASE_A, PHASE_B, and PHASE_C individually are 20.99, 5.41, and 0.77, respectively. This shows the relative importance of nonthermal broadening in each phase.
We do not use the results of Gaussian line fitting as a prior in the PHASE modeling. Therefore, fitting the data using PHASE is completely independent from the curve-of-growth analysis in the previous section. PHASE takes into account line saturation by Voigt profile fitting; the agreement between the two shows that the effect of saturation in the absorption lines, if any, is negligible for most of the ions. The $K_\alpha$ line of C V indicates saturation, because its column density from the curve-of-growth analysis is smaller than that from PHASE. However, the column densities obtained by combining $K_\alpha$ and $K_\beta$ lines of C V, N VI, and O VII are larger than their respective column densities estimated from PHASE. The method of combining $K_\alpha$ and $K_\beta$ transitions for saturated lines is applicable only when the relevant absorption has one component (Draine 2011). Given that C V, N VI, and O VII contribute in multiple temperature components (Figure 3), the column densities estimated by considering $K_\alpha$ and $K_\beta$ lines together are not valid. This shows the power of PHASE modeling, where the physical parameters of the observed system can be estimated without the confusion of single versus multiple components.

3. Results

The best-fit PHASE model (Table 2) has yielded five interesting results: (1) we have detected a hot gas phase probed by Si XIV and Ne X absorption lines; (2) we have detected the warm-hot phase probed by C VI, O VII, O VIII, Ne IX, and Mg XI absorption lines; (3) we have detected a warm phase probed by C V and N VI absorption lines; (4) we have found supersolar $\alpha$/Fe in the hot and the warm-hot phases and nonsolar abundance ratios of the light elements in all phases; and (5) we have constrained the nonthermal broadening in the hot and the warm-hot phases. Below, we discuss each result in detail.

3.1. Temperature

The temperatures of the three phases differ from each other by more than $3\sigma$ (Figure 4) and span a temperature range of two orders of magnitude (Table 2). C V is present predominantly at the lower temperature ($T_1$—warm phase); C VI, N VII, Ne IX and Mg XI are present only at the intermediate temperature ($T_2$—warm-hot phase); Ne X and Si XIV are present only at the higher temperature ($T_3$—hot phase). N VI contributes to both the warm and the warm-hot phases, and O VIII contributes to both the warm-hot and the hot phases (Figure 3). O VII predominantly comes from the warm-hot phase, and it contributes significantly to the warm phase, in which our PHASE model predicts O V and O VI to dominate.\footnote{N(O V) = 1.5_{-0.0}^{+0.2} \times 10^{14} \text{ cm}^{-2}, N(O VI) = 1.6_{-0.0}^{+0.2} \times 10^{14} \text{ cm}^{-2}, and N(O VII) = 4.6_{-0.2}^{+0.2} \times 10^{13} \text{ cm}^{-2} in the warm phase.}

3.2. Column Density

The equivalent hydrogen column density (modulo solar metallicity of oxygen) $N(H)$ of the three phases are starkly different from one other (Table 2). The warm phase has the lowest $N(H)$ and the hot phase has the highest $N(H)$. There is no noticeable correlation between the temperature and the $N(H)$ in the warm phase (reflected by the contour shape in Figure 4(a)). The warm phase is probed by C V, N VI, and O VII (Figure 3), and the ionization fraction of these ions is almost constant in some portion of the temperature range concerned. That makes the $N(H)$ estimate independent of the temperature in the warm phase. The warm-hot and the hot phases are predominantly probed by O VII and Si XIV (and
Ne X), respectively, whose ionization fractions decrease with temperature in the ranges of consideration. Therefore, for a given column density of O VII, Ne X, and Si XIV the \( N(\text{H}) \) increases with temperature in the warm-hot and the hot phases. As a result, temperature and \( N(\text{H}) \) are positively correlated in the warm-hot and partially in the hot phase (Figures 4(d) and (g)). The \( N(\text{H}) \) is practically insensitive of the temperature in the hot phase above a temperature where all the tracer elements are almost completely ionized.

### 3.3. Line Broadening

We detect nonthermal line broadening in the warm-hot and hot phases (Table 2; Figure 2, middle column). The warm-hot phase has a smaller nonthermal broadening than that of the hot phase. The upper limit of the nonthermal broadening in the warm phase is smaller than those in the other two phases. In the warm and the warm-hot phases, the \( b \)-parameters are constrained from multiple transitions of the same ion (e.g., the \( K\alpha \) and \( K\beta \) lines of C V and O VII). The temperature and the thermal broadening are constrained from the ratio of two ions of the same element (e.g., O VIII and O VII). Thus, the excess in the \( b \)-parameter compared to the thermal component can be constrained independent of the temperature. As a result, the temperature and the nonthermal broadening are not correlated in the warm and the warm-hot phases (Figures 4(b) and (c)). On the other hand, the hot phase is predominantly probed by one ion of a given element (e.g., Si XIV or Ne X). Therefore, for a given \( b \)-parameter, thermal and nonthermal broadening are anticorrelated with each other (Figure 4(h)). The ratios of the nonthermal and the thermal broadening are \( 6^{+3}_{-2} \) and \( 4^{+3}_{-2} \) (90% confidence interval) in the warm-hot and hot phases, respectively.

### 3.4. Abundance Ratios

The observed spectral wavelength range does not contain any line or edge of hydrogen. Therefore, we cannot calculate the metallicity, i.e., the absolute abundances of metals with respect to hydrogen. However, we can determine the metal abundances with respect to each other. Oxygen is the most abundant metal in the solar composition, so we report...
abundance ratios of metals with respect to oxygen. We find that carbon is supersolar in the warm and warm-hot phases, magnesium is supersolar in the warm-hot phase, and neon is supersolar in the hot phase (Table 2, Figure 5). Other elements are consistent with a solar mixture.

Because $\text{[Mg/O]}$ is larger than $\text{[C/O]}$ and $\text{[Ne/O]}$ by more than a factor of 3, and Mg abundance depends solely on the Mg XI line, we investigate if the Mg XI line in ACIS-MEG is overestimated. The EW of the Mg XI line by simultaneously fitting the ACIS-HEG and ACIS-MEG spectra is consistent with the EW from only the ACIS-HEG spectrum within 2σ (see the footnote of Table 1). However, the EW from the simultaneous fitting of the HRC-LETG, ACIS-LETG, and ACIS-MEG spectra is smaller than the EW from only the ACIS-HEG spectrum by more than a factor of 2 (Table 1). Out of these three measurements, we consider the smallest EW (and the column density) of Mg XI as the final value as a conservative estimate. We adjust $\text{[Mg/O]}$ in Table 2 (see the footnote) and Figure 4(f) accordingly. Because the warm-hot phase is dominated by oxygen, other physical properties of this phase remain unchanged. While it does not affect our result and the following discussion qualitatively, the revised $\text{[Mg/O]}$ is at par with other supersolar abundance ratios.

$\text{[C/O]}$ and $\text{[Mg/O]}$ are not correlated and $\text{[Ne/O]}$ is positively correlated with temperature (Figure 4). The ionization fraction of C V and Mg XI are independent of temperature and the ionization fraction of Ne X decreases with temperature in the ranges of the temperature concerned. Therefore, for a given column density of these ions, the behavior of the abundance ratios with temperature is not unexpected.

Fe XVI–Fe XVIII UTA and Fe XXII–Fe XXV lines are expected to be present at $T_2$ and $T_3$ respectively, but are not detected at a significance of better than $1\sigma$ (Figure 5, right panel). By using the upper limit of iron abundance, we can determine the lower limit of the abundance ratios of detected elements relative to iron (Table 2). In the warm-hot phase, $\text{[Mg/Fe]}$ is enhanced, and in the hot phase, $\text{[O/Fe]}$, $\text{[Ne/Fe]}$ and $\text{[Si/Fe]}$ are enhanced.

4. Discussion

The hot phase together with the warm-hot phase was first discovered unambiguously along the sight line toward 1ES 1553+113 (Das et al. 2019b). In this paper, we report the discovery of three temperature components: hot, warm-hot, and warm, for the first time; these have not been observed earlier either in emission or in absorption. Below, we discuss each phase, and its relation to the other two phases, in detail. We constrain the nonthermal line broadening of highly ionized CGM phases for the first time. We discuss the role of nonthermal sources in the context of the line broadening. The nonsolar abundance ratios have also not been measured earlier in absorption except along the sight line toward 1ES 1553+113 (Das et al. 2019b). We qualitatively interpret the chemical composition in terms of metal enrichment, mixing, and depletion. These provide interesting insights on the Galactic thermal and chemical evolution and may affect the mass estimation of metals and baryons in the Galactic halo.

We have measured two sets of abundance ratios: (1) the abundance ratio of C, N, Ne, Mg, and Si with respect to O and (2) $\alpha$/Fe (Figure 5). In our analysis, we adopt the solar composition model of Asplund et al. (2009). The result does not change qualitatively if we use the relative solar abundances from Wilms et al. (2000) or Lodders (2003). This is not surprising, because the differences among the composition prescriptions are smaller than the statistical uncertainty of the parameters in our PHASE model.

Please note that the abundance patterns in our observed gas phases do not necessarily reflect that from stellar nucleosynthetic yields. Metals in the ISM come from different sources e.g., winds and flares of stars in different phases of their age, core-collapse supernovae (CCSNe), and Type Ia supernovae (SNe Ia), novae, globular clusters, etc. Different sources

\[16 \text{ MEG has higher spectral resolution and the LETG data have higher S/N. Therefore, they are complementary to each other in this case.}\]
produce and contribute metals to the ISM in different timescales, epochs, and multiple generations/populations (Nomoto et al. 2013). The galactic wind, which carries metals from the ISM to the halo is not homogeneously mass-loaded for all metals (e.g., Lopez et al. 2020). The metal-enriched outflow is further mixed with the preexisting lower metallicity gas in the halo. As a result, it is unlikely that the distribution of metals in the CGM would quantitatively trace/follow any stellar source of metals. Moreover, if the metals in the CGM are inhomogeneously mixed across phases (as has been observed in cooler phases of the CGM traced by CIV; Schaye et al. 2007), our measured chemical composition along a single sight line might be different from the global average. Nonetheless, we try to draw some qualitative inferences from the abundance ratios of metals obtained from our model.

4.1. Warm-hot Phase

The presence of the warm-hot phase with log \( T/(K) \approx 6 \) is known from X-ray absorption-line studies (Gupta et al. 2012, 2014; Nicastro et al. 2016a, 2016b; Gupta et al. 2017; Nevalainen et al. 2017; Gatuzz & Churazov 2018; Das et al. 2019b). The spatial distribution of the warm-hot phase indicates a significant contribution from the Galactic halo beyond the disk (Nicastro et al. 2016a, 2016b; Gatuzz & Churazov 2018). Focusing on the sight line toward Mrk 421, our estimations of the temperature and the hydrogen column density of the warm-hot phase are consistent with those of Gatuzz & Churazov (2018), who assumed a solar metallicity and solar chemical composition in their ionization equilibrium model IONeq. Their three-temperature model is equivalent to \( t_{\text{babs}} \) and the one PHASE component in our model, containing the cold/cool ISM and the warm-hot CGM.

The nonthermal line broadening is consistent with theoretical simulations predicting that the highly ionized CGM is turbulent (Rennoehan et al. 2019; Bennett & Sijacki 2020) and that other nonthermal sources of motion such as magnetic fields and cosmic rays also affect the velocity dispersion (Ji et al. 2020; van de Voort et al. 2021). The ratio of the nonthermal to thermal broadening (see Section 3) indicates the equipartition between the thermal and the nonthermal sources, or the dominance of the nonthermal source if only one kind of nonthermal source is present.

4.1.1. Abundance Ratios

Mg entirely comes from CCSNe (Nomoto et al. 2013), therefore the large value of \([\text{Mg}/\text{O}]\) (and consequently supersolar \([\text{Mg}/\text{Fe}]\)) may indicate CCSNe enrichment. However, a supersolar \([\text{O}/\text{Fe}]\) also is expected in that case but is not observed. This inconsistency may be resolved as follows. The higher emissivity of oxygen compared to Mg at \( T > 10^6 \) K (Bertone et al. 2013) implies that oxygen can cool more efficiently. In an inhomogeneously mixed CGM, oxygen can transit to cooler phases without affecting the temperature of other elements, resulting in an apparent deficit of oxygen. This has been observed in the transition temperature phase of the CGM traced by OIV and O V (Nevalainen et al. 2017) and has been indirectly suggested by cosmological simulations (Ford et al. 2016; Grand et al. 2019).

The \( \alpha \)-enhancement in the warm-hot Galactic CGM has been observed in emission studies (Nakashima et al. 2018), though with poor constraints and chances of confusion with foreground emission. In external galaxies, the \( \alpha \)-enhancement has been observed along the minor axes and in extraplanar regions within 30 kpc of the galactic disks; this suggests that the \( \alpha \)-enhancement is associated with the galactic wind or fountain (Strickland et al. 2004; Yamazaki et al. 2009; Hodges-Kluck et al. 2020; Lopez et al. 2020). The \( \alpha \)-enhancement along our Mrk 421 sight line, with \( T \approx 179^\circ 83 \), indicates several possibilities:

(1) Active galactic outflow resulting from CCSNe feedback may exist toward/around our line of sight. Alternatively, the metals from past nuclear outflows, as indicated by the Fermi bubble and the eROSITA bubble (Predehl et al. 2020; Su et al. 2010), may have spread far from the minor axis of the MW.

(2) Iron is depleted onto interstellar dust that forms within 300–600 days after CCSNe explosions (Todini & Ferrara 2001), leading to iron deficit in outflows. This has been found previously in the X-ray absorption spectra of Galactic low-mass X-ray binaries (Pinto et al. 2013). Alternatively, iron may be depleted onto extraplanar/circumgalactic dust. This process is stable, because there is a low chance of evaporation due to the low-density (\( 10^{-4} – 10^{-3} \) cm\(^{-3} \)) environment (Tielens et al. 1994). This is substantiated by a larger fraction of CGM metals (42\%) in the solid phase compared to that in the ISM (~30\%) in external galaxies (Howk & Savage 1999; Ménard et al. 2010; Peeples et al. 2014).

The depletion of iron onto dust is linked with outflow activities; therefore we cannot determine the relative importance of these two possibilities separately.

4.2. Hot Phase

The strong Si IV and Ne X lines detected in the high-S/N spectra have led us to discover the hot \( (T_\text{h}) \) component. Our observations by themselves cannot determine if the hot phase resides in the Galactic ISM, CGM, or in the Local Group medium. We investigate different possible sources of the observed hot phase to make a reasonable case.

(A) Our sight line is at high altitude \((b = 65^\circ 03)\), passing through a small portion of the Galactic disk. Therefore, the chance of the hot phase coming exclusively from the disk is small. The sight line is anticenter \((l = 179^\circ 83)\), so there is no contribution from the X-ray shell around the Fermi bubble, North Polar Spur (Katoaka et al. 2018), or the eROSITA bubble (Predehl et al. 2020). Moreover, dense structures such as supernova remnants (SNRs) or superbubbles made by expanding and merging SNRs should have detectable emission measure due to their high density. But, the X-ray emission studies along/close to our sight line have not found any such structure yet (Yao & Wang 2007a; Gupta et al. 2014; Sakai et al. 2014). This implies that the contribution of SNR or superbubbles to the hot gas, if any, is unlikely to be significant.

(B) We investigate whether the hot gas is from the Local Group. Assuming the Local Group mass \( = 6.4 \times 10^{12} M_\odot \) (Peebles 1990) and using the \( T_\text{X}^{-1} M \) relation for galaxy clusters: \( T_\text{X} \propto M^{2/3} \), the temperature of the Local Group is \( \approx 10^6 \) K. This is smaller than \( T_\text{h} > 3 \times 10^5 \) K (see Figure 4, bottom panel). Moreover, our sight line \((l = 179^\circ 83, b = 65^\circ 03)\) is away from M31 \((l = 121^\circ 17, b = -21^\circ 57)\) and the barycenter of the Local Group. Therefore, the contribution of the Local Group to the hot phase, if any, is unlikely to be significant. The CGM of MW-like halos of \( M_{200} \approx 10^{12} M_\odot \) can be extended beyond the virial radius \( (R_{200}) \) if the thermal feedback buoyantly rises to the outer
CGM and moves the baryons out (Oppenheimer 2018). Therefore, if the observed hot gas is extended beyond $R_{200}$, it is just a matter of nomenclature whether it should be called the CGM or the Local Group medium. In either case, the gas would be out of thermal and hydrostatic equilibrium due to its higher temperature than the virial temperature of the MW CGM and the Local Group.

(C) The hot phase might originate from active outflows driven by stellar winds and SNe expanding into the halo. The X-ray emission analysis of the nuclear outflow from M82 indicates the coexistence of a hot phase with the warm-hot phase (Ranalli et al. 2008; Lopez et al. 2020). Using the physical parameters of the outflow derived in those analyses, we calculate the approximate column density of a similar outflow if it is observed from the location in the disk. The resulting column density at solar metallicity $\approx 2.8 \times 10^{20} \text{ cm}^{-2}$ is consistent with that of the hot phase within $2\sigma$ (Figure 4(g)). While the MW is not a starburst galaxy, unlike M82, the consistency in the column densities indicates that the possibility of an outflow cannot be ruled out. Because the column density is degenerate with the density and the path length, a different combination of these parameters (e.g., an outflow with lower density and larger volume) might produce the same column density. A careful search for any emission signature around $\approx 1 \text{ keV}$ toward/close to our sight line would test this scenario (S. Bhattacharyya et al. 2021, in preparation).

There have been hints of hot gas in the halo of the MW in emission away from the Galactic center (Yoshino et al. 2009; Mitsuishi et al. 2012; Henley & Shelton 2013; Nakashima et al. 2018; Gupta et al. 2021). It shows that the hot gas can be present without any relation to the nuclear activity of the Galaxy. However, the emission from the hot gas may be confused with the charge-exchange emission and/or the overabundance of metal(s); this is not an issue in absorption analyses. The unambiguous presence of the hot gas in absorption shows that the hot gas is truly widespread.

Similar to the warm-hot phase, the line broadening in the hot phase indicates significant contribution from nonthermal sources (see Section 4.1). The ratio of the nonthermal to the thermal broadening in the warm-hot and hot phases is similar (see Section 3); this indicates that these two phases are related to/influenced by each other.

The $\alpha$-enhancement and the values of [Ne/O] and [Si/O] are consistent with CCSN enrichment (Nomoto et al. 2013). It favors the possibility of an outflow rather than preexisting gas in the halo (or beyond). This was also observed in the $10^7$ K hot phase along 1ES 1553+113 (Das et al. 2019b).

Our temperature estimates are subject to the assumption that the gas is in CIE. However, the hot gas is not at the virial temperature of the MW or the Local Group and is likely related to galactic outflows. Therefore, it might not be in an equilibrium state. If the gas producing the Si XIV and Ne X absorption lines is photoionized, it would affect the derived physical quantities of the hot phase. The effects of the nonequilibrium collisional ionization and photoionization are degenerate in metal-enriched cooling gas (Oppenheimer & Schaye 2013). Therefore, estimating their individual contribution to the hot phase, if any, is nontrivial and beyond the scope of this paper.

### 4.3. Warm Phase

The C IV Kα and Kβ lines have led to the detection and characterization of the warm ($T_1$) component for the first time in X-ray absorption. This phase is usually observed in UV probed by primarily O VI (and sometimes Ne VIII). Similar to the case of the hot phase, we cannot determine the location of the warm phase along our line of sight and cannot say whether it is cospatial with the warm-hot phase.

#### 4.3.1. Carbon Lines

The warm phase produces C IV in addition to C V, and our PHASE model predicts $N$(C IV)$_X = 8.97^{+0.76}_{-0.42} \times 10^{12} \text{ cm}^{-2}$. The $N$(C IV) measured in high-velocity clouds (HVC; $v_{LSR} = 100--500 \text{ km s}^{-1}$) using UV absorption along the same sight line is $N$(C IV)$_{UV} = 5.89 \pm 1.22 \times 10^{12} \text{ cm}^{-2}$ (Richter et al. 2017). These two are consistent with each other within $2\sigma$, but our model predicts $N$(C IV)$_X - N$(C IV)$_{UV} = 3.08^{+1.84}_{-1.54} \times 10^{12} \text{ cm}^{-2}$ of excess $N$(C IV). We cannot apply any velocity cut in our X-ray analysis; therefore this excess absorption, if present, is likely to originate in low-/intermediate-velocity absorbers in the disk/halo. The UV C IV/HVC observations suggest that the warm phase resides in the halo rather than in the disk. It also indicates that the detected C IV in UV along this sight line is unlikely from a cool ($10^4 < T < 10^5$ K) phase coprobed by C II, as was assumed in Richter et al. (2017). This reinstates the reason to study multiple metal lines in X-ray absorption and also shows the power of mult wavelength analysis.

#### 4.3.2. Oxygen Lines

The warm phase also produces O V and O VI along with O VII (see Section 3). Our PHASE model predicts $N$(O VI) = $1.82^{+0.14}_{-0.27} \times 10^{13} \text{ cm}^{-2}$. But $N$(O VI) measured in UV absorption along the same sight line is (2.66–3.15) $\times 10^{14} \text{ cm}^{-2}$ (Williams et al. 2005; Yao & Wang 2007b), a factor of $\approx 2$ larger than our prediction. That means the warm phase does not account for all the O VI detected in UV. Assuming that the absorption feature at 22.03 Å in our spectrum is due to the O VI Kα line only, the total $N$(O VI) is $2.15^{+0.53}_{-0.50} \times 10^{15} \text{ cm}^{-2}$, larger than that from UV analysis by an order of magnitude. This is due to the blending of the O II Kβ line at 20.4 Å, which accounts for most of the absorption (Mathur et al. 2017). To test if the excess O VI in UV is due to photoionization, we reft the X-ray spectrum with the photoionization parameter $U$ of the warm phase frozen at $10^{-3}$, $10^{-2}$, and $10^{-1}$. The best-fit models have worse $\chi^2$/dof than that of the best-fit model with $U = 10^{-4}$, indicating that the latter describes the spectrum better. Moreover, none of the models with a higher value of $U$ can account for the excess O VI measured in UV. This suggests that something other than photoionization might be affecting the warm phase, making it deviate from CIE. This is consistent with previous findings (Lochhaas et al. 2019), where modeling the tracer ions of this phase in the Galactic halo indicated the effects of radiative cooling or nonthermal sources, e.g., turbulent mixing.

The upper limit of the nonthermal broadening in the warm phase (Figure 4(b)) indicates that nonthermal sources are not as strong as they are in the hotter phases, if at all present. While

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17 There was a suggestive evidence of this phase in Williams et al. (2005), but our measurement is more unambiguous due to better quality of data, larger spectral coverage, and self-consistent ionization modeling to simultaneously fit all phases.

18 Because the ionization effect of the temperature and the photoionization are degenerate with each other (Oppenheimer & Schaye 2013), we freeze $U$ at different values instead of allowing both the temperature and $U$ to vary.
the detailed effect of each source of nonthermal motions (turbulence, magnetic fields, cosmic ray) on the physical properties of the CGM is different, all of them enhance the cooling of the hot halo gas and generate cooler and denser phases to balance the total (thermal and nonthermal) pressure against gravity (Bennett & Sijacki 2020; Ji et al. 2020; van de Voort et al. 2021). It implies that the nonthermal broadening in the warm-hot and the hot phases is a natural indicator of coexistent phase(s) at lower temperature. This is consistent with the picture of the warm gas having formed from the cooling of the warm-hot phase.

If the warm phase is clumpy/cloudy instead of diffuse, the phase structure might be more complex. Instead of a uniform warm phase, individual clouds may contain a different combination of metal ions at different temperatures. In that case, the average [C/O] would not be informative and physically meaningful. The supersolar [C/O] might be due to the deficit of oxygen because of its preferential cooling and inhomogeneous mixing of metals while cooling from hotter phases, as discussed in the case of the warm-hot phase (see Section 4.1.1).

4.4. An Emerging Picture

The combined analysis of X-ray emission and absorption toward 1ES 1553+113 indicated the coexistence of at least three temperatures between \( \approx 10^5 - 10^6 \) K (Das et al. 2019a, 2019b). Our results in this paper are consistent with this picture. The temperature of the phases spans more than two orders of magnitude: therefore it is unlikely to be a result of local temperature fluctuation or temperature dispersion in a single phase as is often assumed in theoretical simulations (e.g., Faerman et al. 2017; Li & Tonnesen 2020).

In cosmological zoom-in simulations and idealized simulations of individual galaxies (see their comparative analysis in Fielding et al. 2020), the CGM of an MW-like galaxy is predicted to be a diffuse, volume-filling, low-density, massive warm-hot medium that is cooling due to thermal and hydrodynamic instability, resulting in a structure distributed over a large range of density and temperature. The lower-ionization phases at \( T = 10^{6-7} \) K and predominantly neutral phase at \( T < 10^5 \) K are visualized as dense, clumpy structures that are cooled from and embedded in the hotter medium, with the intermediate-ionization warm phase at \( T = 10^{5-6} \) K at the interface (Marasco et al. 2013; Voit et al. 2015; Armillotta et al. 2017; Strawn et al. 2021).

Most of the observational studies have focused on the oxygen lines (O VI, O VII, and O VIII) in the \( > 10^5 \) K phases. However, the \( 10^7 \) K gas is not detectable with oxygen-only analysis because oxygen is fully ionized by that temperature. Detection of other heavier ions with weaker lines is required to uncover the hot gas, which is difficult to do with low-SNRE spectra. Therefore, the apparent lack of 10^7 K gas in observations of the MW and MW-like galaxies might be an observational bias. Existing simulations (e.g., Ford et al. 2016; Nelson et al. 2018; Wijers et al. 2019) have successfully reproduced the observed lines of oxygen. However, most of the papers do not predict the physical properties of the hot gas, such as the density and path length. Recently, a realistic outflow model including the interaction between the outflow and the halo of an MW-like galaxy has been able to reproduce the \( 10^7 \) K gas for SFR = 10 \( M_\odot \) yr\(^{-1}\), but for an MW-like SFR, the \( 10^7 \) K gas is still not abundant (Vijayan & Li 2021). This indicates the need for improved modeling of thermal feedback of galactic outflows and/or nonthermal heating by turbulent dissipation, magnetic field reconnection, and cosmic rays (Reynolds et al. 1999; Jana & Nath 2018), and high spatial resolution to resolve the complex phase structure of the CGM of an MW-like galaxy and consistently produce the \( 10^7 \) K gas.

The temperature we calculate for the diffuse medium is the density-weighted radial average of the temperature: \( T = \int n(l)T(l)dl/\int n(l)dl \), where \( T(l) \) and \( n(l) \) are the temperature and the hydrogen number density distribution along our line of sight, respectively. For a clumpy medium, it is the average of individual clouds where the variation in temperature is more like a fluctuation rather than a smooth distribution. Additionally, there might be a metallicity gradient. We do not have sufficient information to estimate the parameters of the density/temperature/metallicity distribution and the path length independently.

The temperature estimate is generally biased by the most abundant ion in that phase, e.g., C V and O VII in the warm and the warm-hot phases, respectively. Different metal ions in a given phase need not be coplanar; they may occupy a higher/lower-temperature region according to their ionization fraction. This would underestimate the expected ionization fraction of the less abundant element at the best-fit temperature and would overestimate its abundance ratio with respect to the most abundant element. This may partially explain the high [C/O] and [Mg/O] in the warm and warm-hot phases, respectively.

The three discrete phases in our model is a simplified picture of the \( > 10^5 \) K CGM. Due to the limited baseline in the observed spectra, our results are restricted to a certain range of temperature. The absolute metallicities, the morphology, and the density distribution of the observed system are degenerate with the temperature. This makes the estimation of a more realistic and meaningful phase structure along a single sight line extremely challenging. For theoretical purposes, the best-fit value and the statistical uncertainty of a parameter (see Table 2) can be used as the proxy of the peak and the dispersion of its (e.g., log-normal) distribution, respectively. However, the contours in Figure 4 show that the uncertainties are sensitive to the type of correlation between different parameters, so this approximation should be used with caution. We need to model a larger sample of sight lines across the sky to get a better handle on the parameters and their global dispersion; this would be the part of a future endeavor.

From the above discussion, we infer the following picture of the MW CGM. The hot gas is the metal-enriched, dense, nearby phase tracing galactic wind expanding into the halo. In that case, the actual column density of the hot phase would be smaller because the column density is inversely proportional to metallicity, \( N(H)z = N(H)z_{\odot} \times (Z/Z_{\odot})^{-1} \). There are additional nonthermal sources of heating in the hot phase. The warm-hot phase is the quasi-static phase in the halo where nonthermality is induced by the outflow. The warm phase is tracing clouds or the outer layer of cooler clouds embedded in the hot and the warm-hot phases, outflowing and/or inflowing. This, albeit under a lot of assumptions, could be the emerging picture of the Galactic CGM.

4.5. Missing Galactic Baryons and Metals

Studies involving absorption analysis indicate that the extended warm-hot CGM of the MW likely accounts for all the missing Galactic baryons (Gupta et al. 2012; Nicastro et al.
2016b). However, emission analysis shows that the warm-hot phase is dominated by the disk whose mass is insufficient to account for the missing Galactic baryons (Kaaret et al. 2020). This suggests that the emitting and the absorbing warm-hot gas do not sample the same space in the Galaxy, and their masses should be estimated separately. Second, as discussed in Section 2.3 (also see Table 1), the column density (and the mass) would be overestimated if it is obtained by assuming a single phase. Therefore, the multiphase ionization modeling is crucial to correctly estimate the column density, metallicity, mass, and the total baryonic mass (for a given metallicity) of the warm-hot phase.

The baryonic and the metallic mass of the hot phase has not been estimated yet. Including Mrk 421, the 10^7 K gas has been detected along 11 sight lines in X-ray absorption and/or emission analyses across the sky (Yoshino et al. 2009; Mitsuishi et al. 2012; Henley & Shelton 2013; Das et al. 2019a, 2019b; Gupta et al. 2021). There are no reported nondetections of this phase where it has been searched for. As a result, we do not know the covering fraction of the hot phase. Its mass would be sensitive to its metallicity and density distribution, and to its path length, i.e., whether it is confined in the extraplanar region or is extended out to a significant fraction of the virial radius. Nonetheless, its column density and emission measure along the 11 sight lines suggest that it will contribute a nonnegligible amount to the Galactic budget of baryons and metals.

4.6. Dispersion Measure

The dispersion measure (DM) of fast radio bursts (FRBs) is a promising tool to probe the ionized baryons in the intergalactic medium (IGM) and the CGM of external galaxies (Li et al. 2019; Prochaska & Zheng 2019). For any extragalactic calculation, it is necessary to remove the Galactic contribution, DM_{Gal, from the total observed DM toward an FRB. The current estimate of DM_{Gal based on X-ray absorption and emission studies (Prochaska & Zheng 2019; Yamasaki & Totani 2020; Das et al. 2021) includes the contribution of the warm-hot phase only. The hot phase will increase the DM_{Gal along and around the directions where this phase is present. This will significantly impact the extragalactic studies using the DM of FRBs. As mentioned in Section 4.4, estimating the physical properties of the hot phase and its contribution to the DM_{Gal across the sky would be part of a future endeavor.

4.7. Intervening Absorption?

The low-redshift IGM is believed to be warm hot, detectable through absorption lines of highly ionized metals (Nicastro et al. 2002; Mathur et al. 2003, and references therein). The path length for detecting intervening absorption lines toward Mrk 421 at z = 0.031 is small, but the blazar is X-ray bright, offering an interesting opportunity. Nicastro et al. (2005) reported the detection of two intervening absorption systems, possibly from the warm-hot IGM (WHIM), at z_1 = 0.011 ± 0.001 and z_2 = 0.026 ± 0.001. Their best z_1 line, detected at 3.8σ, is O VII Kα with EW = 3.0 ± 0.8 mÅ. We do not detect this line in the extremely high-S/N spectrum reported here; the 3σ upper limit is 3.1 mÅ. The best z_2 line in Nicastro et al. (2005) is the N VII Kα line at 3.1σ significance with EW = 3.4 ± 1.1 mÅ. We do not detect this line either, with the 3σ upper limit of 1.9 mÅ. Also, we do not detect any other z_2 line. However, we detect the O VIII Kα line at z_1 with EW = 2.2 ± 0.6 mÅ, which is consistent with the upper limit of 4.1 mÅ in Nicastro et al. (2005). We tentatively detect a Si XIV Kα line at z_1 with EW = 0.9 ± 0.3 mÅ, which was not reported in Nicastro et al. (2005). If true, the nondetection of O VII and the detection of O VIII and Si XIV might indicate a hotter WHIM. Similarly, we detect the O VIII Kα line at z_2 with EW = 2.2 ± 0.6 mÅ, which is consistent with the upper limit of 1.8 mÅ within 1σ (Nicastro et al. 2005). Thus, the detection of intervening absorption in the Mrk 421 sight line remains inconclusive.

5. Conclusion

In this paper, we have studied the z = 0 absorber(s) in the deep X-ray grating spectra toward Mrk 421, covering a large wavelength range of 5–43 Å. Our analysis has produced a wealth of important results presented below:

1. We detect a hot ≈10^7 K gas phase probed with Si XIV and Ne X. This phase coexists with the warm-hot 10^6–10^7 K and the warm 10^5–10^6 K CGM along this sight line. This is the first time that a three-phase highly ionized CGM has been detected and characterized in detail by absorption analysis.
2. The hotter phases have higher hydrogen column density than the warm phase, for solar metallicity of oxygen. This indicates that the hotter phases might have higher metallicity/density/path length than the warm phase.
3. For the first time, we have been able to constrain the nonthermal line broadening of any highly ionized CGM phase. The warm-hot and the hot phases of the CGM have nonzero nonthermal line broadening. The nonthermal broadening dominates the broadening of the metal lines.
4. The abundance ratios of metals in the CGM are inconsistent with a solar-like chemical composition:

(a) The hot CGM is significantly α-enhanced, likely due to CCSN enrichment and/or Fe depletion onto dust. [Ne/O] and [Si/O] are supersolar in the hot phase and are consistent with CCSNe enrichment.
(b) [Mg/Fe] and [Mg/O] are significantly supersolar in the warm-hot phase, suggesting evidence of CCSNe enrichment and preferential cooling of oxygen to lower temperature.
(c) [C/O] is supersolar in the warm phase. This could be due to inhomogeneous mixing in clouds while cooling from hotter phases or a complex phase structure of clouds in the 10^4–10^9 K range. These results provide insights into the thermal history, nonthermal effects, chemical enrichment, mixing, and depletion in the circumgalactic medium and provide important inputs to theories of galaxy evolution.

It is necessary to extend such deep X-ray absorption analysis to many other sight lines to search for and characterize the temperature, column density, kinematics, and chemical composition of the highly ionized CGM, using multiple tracer elements along with oxygen. At present, the archival data of Chandra and XMM-Newton can be very useful in this regard. On a longer timescale, upcoming missions like XRISM, Arcus, and Athena and concept missions like Lynx in the next decade
and beyond will offer an outstanding opportunity to observe the highly ionized diffused medium in unprecedented detail. Semianalytical/high-resolution numerical simulations should also look for multiphase highly ionized CGM to explain the observations. This will bring us closer to understanding the coevolution of the Galaxy and its CGM.

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**Data and Model Availability**

We have used public archival data in our analysis. The reprocessed and stacked data and the continuum model are available from the corresponding author upon request.

**Appendix A**

**Continuum Fitting of Mrk 421**

We start the analysis by fitting the global continuum. It is modeled as a variable index power law, absorbed by the cold Galactic ISM (eplogpar*tbabs). The commonly used models such as power-law, broken power-law, and blackbody or their combination do not fit the continuum well ($\chi^2$/dof $\gg 1$). Therefore, we include eplogpar, a power law with an index that varies with energy as a log parabola. This function is used to explain sources of electron acceleration in BL Lac objects (Tramacere et al. 2007; Goswami et al. 2020). The source continuum is absorbed by the Galactic ISM; we describe that with the Tuelingen–Boulder ISM absorption model (Wilms et al. 2000). This model calculates the cross section for X-ray absorption due to the gas phase, the grain phase, and the molecules in the ISM. It assumes solar metallicity and solar-like chemical composition and includes high-resolution structures for the K-edges of oxygen, neon, and the L-edges of iron.

To fit the residual curvatures in the global continuum that likely arise due to calibration uncertainties, we include broad, resolvable Gaussian profiles with both positive and negative normalization as needed and as has been done previously (Nicastro et al. 2002; Williams et al. 2005). We allow the wavelength, width, and normalization of these profiles to vary.

There are several $>3\sigma$ narrow residual decrements not at the locations of $z=0$ He-like and H-like metals. We model them with unresolved Gaussian absorption profiles. We list the wavelength, EW, and possible identification of these lines in Table A1, and these are discussed further below in Appendix B.

We define the pseudocontinuum as defined above and then look for the $z=0$ absorption lines from the MW CGM. For our model-independent study, it is sufficient to fit the local continuum around the strongest transitions of He-like and the H-like metal ions. But, our ionization modeling (see Section 2.3) includes weaker transitions of these ions in addition to the stronger ones, which are spread across the global continuum. These transitions are not individually detectable, but the constraint on their strength makes the estimation of the physical parameters more precise and self-consistent than the model-independent analysis. This justifies the detailed fitting of the global continuum before searching for the He-like and the H-like metal ions.

**Appendix B**

**Absorption Lines Not from the Milky Way CGM**

As noted in Appendix A, there were other absorption lines in the spectrum that were not at the location of the $z=0$ He-like and H-like metal lines. These are listed in Table A1, and we discuss them here.

Some of these “other” lines are from the putative intervening absorbers at $z = 0.011$ (see discussion in Section 4.7). The 10.24 Å line could be a blend of Ne X Kβ (10.24 Å; Erickson 1977) and 2s → 3d transition of Ni XXIV (10.28 Å; Verner & Yakovlev 1995); this is the first astronomical identification of this line to our knowledge.

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**Table A1**

| Wavelength (Å) | EW (mA) | Identification |
|---------------|---------|----------------|
| 6.26          | 0.88±0.29 | Si XIV $\alpha$=0.01? |
| 10.24         | 1.67±0.28  | Ne X+Ni XXIV ? |
| 19.15         | 2.17±0.61  | O VIII $\alpha$=0.01 |
| 19.51         | 2.18±0.64  | O VIII $\alpha$=0.026 |
| 22.02         | 3.79±0.87  | O II+O VI |
| 22.29         | 3.07±0.87  | O II+O VI |
| 25.20         | 2.78±0.43  | unidentified/spurious a |
| 26.94         | 2.72±0.65  | unidentified |
| 29.04         | 2.57±0.67  | unidentified/spurious a |
| 30.15         | 2.15±0.76  | unidentified/spurious |
| 30.53         | 2.22±0.81  | N III Kα |
| 30.92         | 7.02±0.26  | N II Kα |
| 31.00         | 5.15±0.34  | N II Kα |
| 31.28         | 3.78±0.82  | N I Kα |
| 40.04         | 5.20±0.67  | C II ? |
| 40.34         | 7.56±1.36  | C II ? |

Note. The uncertainties in the wavelengths are the same as the resolution elements, i.e., 12.5 mÅ for ACIS-MEG, and 25 mÅ for ACIS-LETG and HRC-LETG. Unidentified lines are likely the transitions of lower-ionization states of light elements (e.g., Si, S, Ar, Ca, etc.) from the cold/cool Galactic ISM (see AtomDB, www.atomdb.org). The equivalent width of spurious lines is $>2\sigma$ different between positive- and negative-order spectra, implying that they are likely caused by bad pixels.

a K-shell transitions of NV have been predicted at these wavelengths (García et al. 2009). But, as the strongest transition of NV Kα at 29.42 Å is not detected in our spectra (Figure 1, bottom), these are unlikely to be NV lines.
We detect two blends of the O VI and O II K-shell transitions likely dominated by O II: O II K\(\beta\) (22.04 Å; Bizau et al. 2015) and O VI K\(\alpha\) (22.03 Å; McLaughlin et al. 2017; see further discussion in Section 4.3.2); and O II K\(\beta\) (22.30 Å; Bizau et al. 2015) and O VI K\(\alpha\) (22.30 Å; Liang & Badnell 2011). We detect N I–N III K\(\alpha\) lines at 30.53–31.28 Å (García et al. 2009; Gatuzz et al. 2021). The absorption at 40.04 and 40.34 Å could be weaker K-shell transitions of C II (Hasoglu et al. 2010; Gatuzz et al. 2018). The strongest transition of the C II K\(\alpha\) triplet between 42.7 and 43.2 Å is shown in Figure B1. The detection of strong C II, N I–N III, and O II lines indicates that these transitions are underestimated by tbabs, suggesting supersolar carbon, nitrogen, and oxygen in the Galactic cold/cold ISM toward Mrk 421. Other equivalent ISM models in XSPEC (e.g., wabs, phabs, ISMabs, etc.) do not include all the low ions of carbon, nitrogen, and oxygen in full capacity either. Therefore, replacing the tbabs model does not improve the situation. Precise information about these ion transitions, e.g., the wavelength, photo-absorption cross section, etc. are still a topic of active research, and often, well-understood astrophysical sources are used for benchmarking. Because our science interest is not focused on the physical properties of the cold/cold ISM, we do not discuss this further in the main text.

This leaves us with four lines that are unidentified and/or spurious. To further test these possibilities, we looked for the line signatures in both positive and negative orders of the gratings. The line at 26.94 Å was detected in both the orders; therefore it is unlikely to be spurious. We report this line as “unidentified” in Table A1. Several lines reported in Table A1 were identified for the first time in the past few years. This is an emerging field, therefore it is quite possible that the unidentified lines will be identified in the years to come. However, we cannot rule out the possibility that the remaining three lines are truly spurious. The HRC-LETG spectrum has 784 resolution elements. Therefore, we expect to detect two lines with >3\(\sigma\) significance by chance, as observed at 25.2 and 29.04 Å. The third unidentified/spurious line at 30.15 Å is detected with 2.82\(\sigma\) significance, but we report it for the sake of completeness. Despite being a <3\(\sigma\) decrement, we add the 30.15 Å line in our pseudo-continuum model to properly estimate the local continuum (a broad Gaussian between N VI K\(\alpha\) and N III lines) around N VI K\(\alpha\), which is necessary for our science interest. We expect to detect three lines with >2.82\(\sigma\) significance by chance, consistent with our observations.

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**References**

Armillotta, L., Fraternali, F., Werk, J. K., Prochaska, J. X., & Marinacci, F. 2017, MNRAS, 470, 114
Arnaud, K., Dorman, B., & Gordon, C. 1999, XSPEC: An X-ray Spectral Fitting Package, Astrophysics Source Code Library, ascl:9910.005
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009,ARA&A, 47, 481
Bennett, J. S., & Sjijackj, D. 2020, MNRAS, 499, 597
Bertone, S., Aguierre, A., & Schaye, J. 2013, MNRAS, 430, 3292
Bizau, J. M., Cubaynes, D., Guibaud, S., et al. 2015, PhRvA, 92, 023401
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Das, S., Mathur, S., Gupta, A., Nisticò, F., & Krongold, Y. 2019a, ApJ, 887, 257
Das, S., Mathur, S., Gupta, A., Nisticò, F., & Krongold, Y. 2021, MNRAS, 500, 655
Das, S., Mathur, S., Nisticò, F., & Krongold, Y. 2019b, ApJL, 882, L23
Draine, B. T. 2011, Physics of the Interstellar and Intergalactic Medium (Princeton, NJ: Princeton Univ. Press)
Drake, S. A. 2005, in X-Ray and Radio Connections, ed. L. O. Sjouwerman & K. K. Dyer (Santa Fe, NM: NRAO), 601
Dubois, P. F., Hinsen, K., & Hugunin, J. 1996, ComPh, 10, 262
Erickson, G. W. 1977, JPRCD, 6, 831
Faerman, Y., Sternberg, A., & McKee, C. F. 2017, ApJ, 835, 52
Fielding, D. B., Tonnesen, S., DeFelippis, D., et al. 2020, ApJ, 903, 32
Ford, A. B., Werk, J. K., Davé, R., et al. 2016, MNRAS, 459, 1745
Francione, A., McDowell, J. C., Allen, G. E., et al. 2006, Proc. SPIE, 6270, 62701V
García, J., Kallman, T. R., Withbroe, M., et al. 2009, ApJS, 185, 477
Gatuzz, E., & Churazov, E. 2018, MNRAS, 474, 696
Gatuzz, E., García, J. A., & Kallman, T. R. 2021, MNRAS, 504, 4460
Gatuzz, E., Ness, J. U., Gorczyca, T. W., et al. 2018, MNRAS, 475, 2457
Goswami, P., Sahayathan, S., Sinha, A., & Gogoi, R. 2020, MNRAS, 499, 2094
Grand, R. J. J., van de Voort, F., Zijp, J., et al. 2019, MNRAS, 490, 4786
Gupta, A., Galeazzi, M., Koutroumpa, D., Smith, R., & Lallement, R. 2009, ApJ, 707, 644
Gupta, A., Kingsbury, J., Mathur, S., et al. 2021, ApJ, 909, 164
Gupta, A., Mathur, S., Galeazzi, M., & Krongold, Y. 2014, ApJSS, 352, 775
Gupta, A., Mathur, S., & Krongold, Y. 2017, ApJ, 836, 243
Gupta, A., Mathur, S., Krongold, Y., Nisticò, F., & Galeazzi, M. 2012, ApJL, 756, L8
Hasoglu, M. F., Abdel-Naby, S. A., Gorczyca, T. W., Drake, J. J., & McLaughlin, B. M. 2010, ApJ, 724, 1296
Henley, D. B., & Shelton, S. L. 2013, ApJ, 773, 92
Henley, D. B., Shelton, R. L., Kwak, K., and Joong, M. R., and Lallement, R. 2009, ApJ, 707, 644
Hughe, A., Mathur, S., Galeazzi, M., & Krongold, Y. 2014, ApJSS, 352, 775
Krongold, Y., Nicastro, F., Brickhouse, N. S., et al. 2003, ApJ, 597, 832
Kuntz, K. D., & Snowden, S. L. 2000, ApJ, 543, 9
Liang, G. Y., & Badnell, N. R. 2011, ApJ, 733, 92
Li, Z., Gao, H., Wei, J.-J., et al. 2019, ApJ, 876, 146
Li, M., & Tonnesen, S. 2020, ApJ, 898, 148
Li, M., Bryan, G. L., & Ostriker, J. P. 2017, ApJ, 841, 101
Li, M., & Ostriker, J. P. 2020, ApJ, 898, 148
Lim, L., Bryan, G. L., & Ostriker, J. P. 2017, ApJ, 841, 104
Liang, G. Y., & Badnell, N. R. 2011, A&A, 528, A69
Lorchas, C., Mathur, S., Frank, S., et al. 2019, MNRAS, 489, 78
Lodders, K. 2003, ApJ, 591, 1220
Lopez, L. A., Mathur, S., Nguyen, D. D., Thompson, T. A., & Olivier, G. M. 2020, ApJ, 904, 152
Marasco, A., Marinacci, F., & Fraternali, F. 2013, MNRAS, 433, 1634
Mathur, S., Nisar, A., Gupta, A., et al. 2017, ApJL, 851, L7
Mathur, S., Weinberg, D. H., & Chen, X. 2003, ApJ, 582, 82
McLaughlin, B. M., Bizau, J. M., Cubaynes, D., et al. 2017, MNRAS, 465, 4690
Ménard, B., Scarton, R., Fukugita, M., & Richards, G. 2010, MNRAS, 405, 1025
Mitsuishi, I., Gupta, A., Yamasaki, N. Y., et al. 2012, PASJ, 64, 18
Nakashima, S., Inoue, Y., Yamasaki, N., et al. 2018, ApJL, 862, 34
Nelson, D., Kauffmann, G., Pillepich, A., et al. 2018, MNRAS, 477, 450
Nevalainen, J., Wakker, B., Kaasra, J., et al. 2017, A&A, 605, A47
Nicastro, F., Kaasra, J., Krongold, Y., et al. 2018, Natur, 558, 406
Nicastro, F., Mathur, S., Elvis, M., et al. 2005, ApJ, 629, 700
Nicastro, F., Senatore, F., Gupta, A., et al. 2016a, MNRAS, 457, 676
Nicastro, F., Senatore, F., Krongold, Y., Mathur, S., & Elvis, M. 2016b, ApJL, 828, L12
Nicastro, F., Zezas, A., Drake, J., et al. 2002, ApJ, 573, 157
Nomoto, K., Kobayashi, C., & Tominaga, N. 2013, ARA&A, 51, 457
Oppenheimer, B. D. 2018, MNRAS, 480, 2963
Oppenheimer, B. D., Crain, R. A., Schaye, J., et al. 2016, MNRAS, 460, 2157
Oppenheimer, B. D., & Schaye, J. 2013, MNRAS, 434, 1043
Peeples, M. S. 1990, ApJ, 362, 1
Peeples, M. S., Werk, J. K., Tumlinson, J., et al. 2014, ApJ, 786, 54
Pinto, C., Kaasra, J. S., Costantini, E., & de Vries, C. 2013, A&A, 551, A25
Predehl, P., Sunyaev, R. A., Becker, W., et al. 2020, Natur, 588, 227
Prochaska, J. X., & Zheng, Y. 2019, MNRAS, 485, 648
Putman, M. E., Peek, J. E. G., & Young, M. R. 2012, ARA&A, 50, 491
Ranalli, P., Comastri, A., Origlia, L., & Maiolino, R. 2008, MNRAS, 386, 1464
Rennehan, D., Babul, A., Hopkins, P. F., Davé, R., & Mou, B. 2019, MNRAS, 485, 3810
Reynolds, R. J., Haffner, L. M., & Tuft, S. L. 1999, ApJL, 525, L21
Richter, P., Naza, S. E., Fox, A. J., et al. 2017, A&A, 607, A48
Sakai, K., Yao, Y., Mitsuda, K., et al. 2014, PASJ, 66, 83
Schaye, J., Carswell, R. F., & Kim, T.-S. 2007, MNRAS, 379, 1169
Schaye, J., Crain, R. A., Bower, R. G., et al. 2015, MNRAS, 446, 521
Spitzer, L. J. 1956, ApJ, 124, 20
Straw, C., Roca-Fàbrega, S., Mandelker, N., et al. 2021, MNRAS, 501, 4948
Strickland, D. K., Heckman, T. M., Colbert, E. J. M., Hoopes, C. G., & Weaver, K. A. 2004, ApJS, 151, 193
Su, M., Slater, T. R., & Finkbeiner, D. P. 2010, ApJ, 724, 1044
Tieleman, A. G. M., McKee, C. F., Seab, C. G., & Hollenbach, D. J. 1994, ApJ, 431, 321
Todini, P., & Ferrara, A. 2001, MNRAS, 325, 726
Tramacere, A., Massaro, F., & Cavalliere, A. 2007, A&A, 466, 521
Tumlinson, J., Peeples, M. S., & Werk, J. K. 2017, ARA&A, 55, 389
van de Voort, F., Bieri, R., Pakmor, R., et al. 2021, MNRAS, 501, 4888
Verner, D. A., & Yakovlev, D. G. 1995, A&AS, 109, 125
Vijayan, A., & Li, M. 2021, arXiv:2102.11510
Voit, G. M., Donahue, M., Bryan, G. L., & McDonald, M. 2015, Natur, 519, 203
Wijers, N. A., Schaye, J., Oppenheimer, B. D., Crain, R. A., & Nisar, A. 2019, MNRAS, 488, 2947
Williams, R. J., Mathur, S., Nisar, A., et al. 2005, ApJ, 631, 856
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
Yamasaki, N. Y., Sato, K., Mitsuishi, I., & Ohashi, T. 2009, PASJ, 61, S291
Yamasaki, S., & Totani, T. 2020, ApJ, 888, 105
Yao, Y., & Wang, Q. D. 2007a, ApJ, 666, 242
Yao, Y., & Wang, Q. D. 2007b, ApJ, 658, 1088
Yoshino, T., Mitsuda, K., Yamasaki, N. Y., et al. 2009, PASJ, 61, 805