Discovery of a cool, metal-rich gas reservoir in the outskirts of \(z \approx 0.5\) clusters

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ABSTRACT

We built the first-ever statistically significant sample of \(\approx 80,000\) background quasar – foreground cluster pairs to study the cool, metal-rich gas in the outskirts \((> R_{500})\) of \(z \approx 0.5\) clusters with a median mass of \(\approx 10^{14.2}\) M\(_\odot\). The sample was obtained by cross-matching the SDSS cluster catalog of Wen & Han (2015) and SDSS quasar catalog of Lyke et al. (2020). The median impact parameter \((\rho_{cl})\) of the clusters from the quasar sightlines is 2.4 Mpc (median \(\rho_{cl}/R_{500} = 3.6\)). A strong Mg\(\text{II}\), along with marginal Fe\(\text{II}\), absorption is detected in the mean and median stacked spectra of the quasars with total Mg\(\text{II}\) rest-frame equivalent width \((W_{5796+2803}^{\text{rest}})\) of \(0.034 \pm 0.005\) Å (?\(\sigma\)) and \(0.010 \pm 0.003\) Å (?\(3\sigma\)), respectively. The \(W_{5796+2803}^{\text{rest}}\) shows a declining trend with increasing \(\rho_{cl}\) and \(\rho_{cl}/R_{500}\), but does not show any significant trend with mass \((M_{500})\) or redshift \((z_{cl})\) within the small \(M_{500}\) and \(z_{cl}\) ranges probed here. The Mg\(\text{II}\) absorption signal and the trends persist even if we exclude the quasar-cluster pairs where the background quasars may be probing the circum-galactic medium (CGM) of bright galaxies with impact parameters < 300 kpc. The Mg\(\text{II}\) (and Fe\(\text{II}\)) absorption reported here is the first detection of its kind. It indicates the presence of a cool, metal-rich gas reservoir surrounding galaxy clusters out to several \(R_{500}\). We suggest that the metal-rich gas in the cluster outskirts arise from stripped materials and that gas stripping may be important out to large clustocentric distances \((> 3R_{500})\).

Keywords: galaxies: clusters: general – galaxies: clusters: intracluster medium – (galaxies:) intergalactic medium – (galaxies:) quasars: absorption lines

1. INTRODUCTION

Galaxy clusters, being the largest structures in the universe, serve as unique environments for studying galaxy evolution. They are testbeds for cosmological quandaries such as the missing baryons, properties of dark matter and dark energy, and enrichment of the intergalactic medium (IGM; Gonzalez et al. 2007; Allen et al. 2008; Vikhlinin et al. 2009). Estimating how baryons are distributed among different components and phases in clusters is key for understanding the roles played by different physical processes such as starburst winds, supernovae--/AGN-feedback, galaxy mergers, and tidal/ram-pressure stripping in driving galaxy evolution in such complex environments. The majority of the baryons in clusters reside in the inter-cluster medium (ICM) in an X-ray emitting, hot \((\sim 10^7-8\) K) phase (Ettori 2003). Consequently, the central regions of clusters are well studied via X-ray (and GHz) observations (e.g., Bleem et al. 2015; Liu et al. 2021). In addition, sensitive X-ray observations of a handful of nearby clusters have characterized the properties such as the surface brightness, metallicity, and gas fraction out to the virial radii \((R_{\text{vir}}\); Simionescu et al. 2011; Urban et al. 2014). However, owing to the significantly lower density and temperature, the outskirts (i.e., \(1-5 \times R_{500}\)) or the circum-cluster medium (CCM) of galaxy clusters are not well explored. This is primarily because of the lack of sensitive diagnostics in X-rays to probe the cool/warm-hot gas \((\sim 10^{4-6}\) K) that prevails in the CCM.

With the advent of high resolution cosmological hydrodynamical simulations, cluster outskirts have been recognised as an important environment for studying cluster astrophysics and cosmology (Nagai et al. 2007; Lau et al. 2015; Bahé et al. 2017). Being the interface between clusters and the IGM, the CCM acts as “melting pots” where infalling metal-poor gas from the IGM mixes with metal-rich gas when galaxies and groups

\(^1\) \(R_{500}\) is the radius within which the mean mass density of a cluster is 500 times the critical density of the universe.
of galaxies are stripped of via ram pressure and tidal forces. Thus, it is a new frontier for understanding gas flows in and around clusters, and the environmental processes that drive galaxy evolution in clusters (see Walker et al. 2019, and references therein). Using hydrodynamical simulations, Emerick et al. (2015) showed that the majority of the cool/warm-hot gas in cluster outskirts is linked with infalling material through IGM filaments. This, however, changes in the inner clustocentric distances (i.e., in the outskirts). The metallicity of the cool/warm-hot gas in the outskirts shows a large scatter compared to the hot gas fraction at $R \gtrsim 3R_{\text{vir}}$. The latter study by Butsky et al. (2019) also reported qualitatively similar results. They showed that the ICM exhibits an increasingly multiphase nature at large clustocentric distances (i.e., in the outskirts). The metallicity of the cool/warm-hot gas in the outskirts shows a large scatter compared to the hot gas in the cores, owing to the poor mixing of IGM gas with stripped of galactic material. Finally, they found signatures of CGM stripping of cluster galaxies during the early stages of infall at distances as far as $4R_{\text{vir}}$.

There are only a handful of observational studies in the literature focused on the CCM (e.g., Lopez et al. 2008; Yoon et al. 2012; Muzahid et al. 2017; Yoon & Putman 2017; Burchett et al. 2018). The study of Yoon et al. (2012) showed that Lyα absorbers are preferentially located in the outskirts of Virgo clusters and are associated with substructures traced by H I 21-cm emission. Muzahid et al. (2017) reported the presence of partial Lyman limit systems (LLS) with $N$(H I) $\gtrsim 10^{16.5}$ cm$^{-2}$ in the outskirts of 3/3 clusters they studied. Detailed ionization modelling of those absorption systems revealed the presence of metal-enriched gas with metallicities of $[X/H] > -1$ (Pradeep et al. 2019). Burchett et al. (2018) studied the outskirts of 7 clusters but found no significant H I absorption. Using ground-based observations, Lopez et al. (2008) reported an overabundance of strong Mg II absorption with rest-frame equivalent width (REW) of Mg II λ2796 ($W_{\lambda 2796}^R$) $> 2$ Å compared to the “field” Mg II population (see also Lee et al. 2021). By cross-matching catalogs of Mg II absorbers and clusters from Dark Energy Spectroscopic Instrument (DESI) survey, Anand et al. (2022) recently reported a covering fraction of 1–5% within $R_{500}$ for $W_{\lambda 2796}^R > 0.4$ Å. From a lack of correlations between the absorbers and the properties of nearest cluster galaxies (within $R_{200}$), and the fact that the median absorber-galaxy separation is $\approx 200$ kpc, they concluded that Mg II absorption stems from stripped ISM and/or from satellite galaxies.

All of these aforementioned studies dealt either with small sample sizes and/or limited by the sensitivity to detect individual absorbers. To investigate the extent of cool, metal-enriched gas and their dependence on the cluster properties using a statistically significant sample, here we employ spectral stacking technique to a large number ($\approx 80,000$) of quasar-cluster pairs. The paper is organised as follows: In Section 2 we describe the quasar and cluster samples used in this study, followed by the details of the construction of the quasar-cluster pairs, and continuum normalization of the SDSS spectra. The main results are presented in Section 3 followed by a discussion in Section 4. We adopted a flat ΛCDM cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. SAMPLES

2.1. Cluster sample

We use the Sloan Digital Sky Survey (SDSS) galaxy cluster catalog of Wen & Han (2015, hereafter WH15), consisting of 158,103 clusters. The WH15 improves upon the catalog of Wen et al. (2012, hereafter WHL12) and provides the largest number of clusters with spectroscopic redshifts. The masses of the clusters in WH15 are calculated using a scaling relation derived from a sample of 1191 clusters with well-measured masses with $M_{500} > 0.3 \times 10^{14}$ M$_\odot$ and $0.05 < z_{cl} < 0.75$. Therefore, we start with the 156,139 clusters within this mass and redshift ranges. Our requirement of having spectroscopic redshifts reduces the number to 119,653 clusters. To eliminate repeated entries with somewhat different redshifts and sky positions within these clusters, we flag the clusters that met the following criteria: (i) two clusters with a velocity offset $< 1000$ km s$^{-1}$ and (ii) physical separation is less than the sum of their $R_{500}$ values$^2$. We only consider the most massive one if two or more clusters satisfy these two conditions. This results in 118,000 unique clusters.

While no formal completeness estimate is presented in WH15, the WHL12 catalog, which forms the bulk of the WH15 sample, is $> 95\%$ complete for $M_{500} > 10^{14}$ M$_\odot$ and $0.05 < z_{cl} < 0.42$. Note that all the clusters in our sample have $z_{cl} > 0.42$ (Section 2.3) for which the completeness of the cluster catalog is not characterized. However, 88% of the clusters in our sample have $M_{500} > 10^{14}$ M$_\odot$, and the results presented here are consistent if the clusters with $M_{500} < 10^{14}$ M$_\odot$ are excluded.

2.2. Quasar sample

$^2$ Note that we recalculated the $R_{500}$ values using the redshift and $M_{500}$ values from the catalog for our adopted cosmology.
We use the SDSS DR16 quasar catalog of Lyke et al. (2020) to cross-match with the cluster catalog. This catalog contains a total of 750,414 quasars. We exclude the spectra with median signal-to-noise (SNR) of < 5, reducing the number to 291,956. We also exclude the spectra with broad absorption lines (BALs) with a non-zero “BALnicity index” (BI) as provided in the catalog of Lyke et al. (2020). This further reduces our sample to 278,580 quasars which is then used to cross-match with the cluster catalog described above. The spectroscopic observations of these quasars are performed using SDSS and Baryon Oscillation Spectroscopic Survey (BOSS) spectrographs. The spectra obtained with SDSS cover a spectral range between 3800–9200 Å with spectral resolution ($R$) ranging from 1850−2200. The BOSS spectra cover a spectral range from 3600–10,000 Å with $R \approx 1300−3000$.

2.3. Quasar-cluster pairs

We cross-match the catalog of 278,580 background quasars with the 118,000 galaxy clusters. We impose the following selection criteria for our quasar-cluster pairs:

(i) The cluster must have a spectroscopic redshift ($z_{cl}$) for which the Mg II doublet should fall in the wavelength range 4000–9000 Å, since the throughputs of SDSS and BOSS drop below 10% beyond this range, (Smee et al. 2013) leading to poor spectral SNR.

(ii) The cluster redshift ($z_{cl}$) is such that the Mg II doublet always falls on the redward of the Ly$\alpha$ emission of the background quasar. This is to avoid contamination from the Ly$\alpha$-forest absorption.

(iii) The line-of-sight velocity offset between the quasar and cluster redshifts is $> 5000$ km s$^{-1}$ to minimize possible contamination due to absorption intrinsic to the background quasar/host-galaxy (e.g., Muzahid et al. 2013).

(iv) The projected separation between the foreground cluster and the background quasar at the redshift of the cluster ($\rho_{cl}$) should lie between $1−5 \times R_{500}$, suitable to probe the CCM.

The aforementioned conditions yield 81,045 quasar-cluster pairs with 64,339 unique quasars and 38,001 unique clusters. In the subsequent analysis, we exclude 887 spectra contributing to 1104 quasar-cluster pairs in which we noticed spectral gaps in our regions of interest. Next, even after excluding the quasars with non-zero BI (Lyke et al. 2020), we found strong BAL features in 326 quasar spectra (284 C iv BAL quasars and 42 Mg II BAL quasars), accounting for a total of 456 quasar-cluster pairs$^3$. After excluding those 456 pairs, our final sample has 79,485 quasar-cluster pairs with 63,126 and 37,632 unique quasars and clusters, respectively.

In Fig. 1, we show the scatter plots of $M_{500}$ vs $z_{cl}$ for the 37,632 unique clusters (bottom), and $\rho_{cl}/R_{500}$ versus $z_{cl}$ for the 79,485 quasar-cluster pairs (top). The cluster redshifts range from 0.43 to 0.75 with a median of 0.54. The $M_{500}$ ranges from $(0.3 − 12.5) \times 10^{14} M_{\odot}$ with a median of $1.5 \times 10^{14} M_{\odot}$. The normalized impact parameter ($\rho_{cl}/R_{500}$) of our quasar-cluster pairs ranges from 1.0 – 5.0 by design, with a median of 3.6. Finally, the median impact parameter of our sample is 2.4 Mpc.

2.4. Continuum normalization

We found that the default SDSS principal component analysis (PCA) quasar continua are not adequate for the

$^3$ We use a method similar to Mishra et al. (2021) to search for C iv and Mg II BAL features.
Figure 2. **Bottom:** The mean composite spectrum of the background quasars at the rest-frame of the clusters for the full sample. The grey 1σ error-bars are estimated from 200 bootstrap realizations. The solid blue line shows the best-fit pseudo continuum. The best-fit Mg II and Fe II absorption profiles are shown in smooth magenta curves. The line centroids are shown by the arrows. **Middle:** Same as the bottom panel but for the median stack. **Top:** Number of quasar-cluster pairs contributing to the stacked spectra as a function of rest-frame wavelength. The four dashed horizontal lines two each around the Fe II and Mg II lines in each panel, respectively, correspond to [2589,2611] Å and [2784,2815] Å wavelength ranges within which the REWs are calculated.

The asymmetric sigma-levels were determined based on the median SNR of each spectrum.

(a) First, we normalize each spectrum by the corresponding PCA continuum. We considered the wavelength range in the observed frame between 3600 to 5300 Å only. This range is sufficient to cover the Mg II doublet along with the Fe II λ2600 and Mg I λ2852 transitions from all of our clusters.

(b) Next, we performed an iterative boxed sigma-clipping with asymmetric sigma-levels on the PCA-continuum-normalized spectrum. This ensures efficient clipping of absorption features while retaining the residual emission line features. The number of boxes was chosen based on the presence/absence of strong emission lines within the wavelength range of our interest.

In Fig. A1, we present a step-by-step illustration of our continuum-fitting algorithm for the quasar SDSS J013346.72−002534. In Fig. A2, we show three examples of quasar spectra with SDSS default continua along
with the improved continua from our new algorithm. It is apparent from Figs. A1 and A2 that our new adopted continua are significantly improved compared to the default SDSS continua.

3. RESULTS

In this study, we use the spectral stacking technique (see e.g., Muzahid et al. 2021) to probe the CCM of the clusters in our sample. For each quasar-cluster pair, we first shift the normalized quasar spectrum to the rest-frame of the cluster by dividing the observed wavelengths by (1 + zcl). We then calculate the mean and median fluxes in bins of 1 Å. To avoid a few bad pixels, we use 50σ clipping. We confirm that our results are not sensitive to either the bin size or the 50σ clipping used here. We focus on the rest-frame 2500–3000 Å spectral range, which covers both the Feii λ2600 and Mgii λ2852 in addition to the targeted Mgii λλ2796,2803 transitions. In the top panel of Fig. 2, we show the number of quasar-cluster pairs contributing to the stacks at each rest-frame wavelength bin. As expected, all the quasar-cluster pairs in our sample are contributing to the stacked profiles near the Mgii wavelengths. However, the number of pairs is reduced for the Feii λ 2600 line.

The mean and median stacked spectra are shown in the bottom and middle panels of Fig. 2, respectively. The Mgii line is clearly detected in both the mean and median stacked spectra with total REW (W_{2796+2803}^{2796}) of 0.034 ± 0.005 Å and 0.010 ± 0.003 Å, indicating 7σ and 3σ detection significance for the mean and median stacks. The two members of the Mgii doublet are barely resolved in the stacked spectra. The REW values are calculated after re-normalizing the stacked spectra by the corresponding pseudo-continua. The pseudo-continuum levels for the mean and median stack spectra are determined by fitting, respectively, 1st and 2nd order polynomials to the line-free regions. Note that the pseudo-continua are consistent with the overall flux decrements when we randomized the cluster redshifts. The uncertainties in the REW are quadrature addition of the pseudo-continuum placement uncertainty and the statistical uncertainty calculated from 200 bootstrap realizations of the full sample.

Assuming that the observed Mgii line falls on the linear part of the curve-of-growth (COG), and only 2/3 of the total REW is owing to the Mgii λ2796 line, 4 we obtained W_{2796}^{2796} of 0.023 ± 0.003 Å (0.007 ± 0.002 Å) and column density of log_{10} N(Mgii)/cm^{-2} = 11.72 ± 0.06 (11.22 ± 0.14) for the mean-stacked (median-stacked) spectrum.

Besides Mgii, marginal Feii λ2600 absorption line is detected with mean (median) REW of 0.010 ± 0.006 Å (0.008 ± 0.003 Å). The corresponding column density is log N(Feii)/cm^{-2} = 11.86 ± 0.24 (11.75 ± 0.17) for the mean (median) stack. We fit the Feii and Mgii lines simultaneously with a three-component Gaussian centered at the Feiiλ2600 and Mgiiλλ2796,2803 lines with the centroids separated by the rest-frame wavelengths of the transitions and by keeping the widths (σv) tied and amplitudes free. The best-fit Gaussian has a velocity centroid (V0) of 55 ± 116 km s^{-1} for the mean-stacked profile (64 ± 73 km s^{-1} for the median), which is fully consistent with 0 km s^{-1}. The measured line widths are 355 ± 36 km s^{-1} and 317 ± 58 km s^{-1} for the mean and median stacks, respectively. The measurements performed on the stacked profiles are summarized in Table 1. Finally, we do not detect any Mgii absorption. Given the extremely high SNR of the stacked spectrum, the non-detection of Mgii implies mean REW(Mgii) < 0.003 Å (3σ), assuming that the undetected line is spread over 8 pixels (2.355×σv, ≈ 840 km s^{-1}).

Next, we produced stacks for three mass and three redshifts bins with a nearly equal number of quasar-cluster pairs in each bin. We did not find any significant dependence of Mgii REW on either mass or redshift, likely due to the narrow ranges of mass and redshift probed here (see 16 and 84 percentiles of the sample distribution from Table 1). Similarly we split the full sample in three bins of ρcl and ρcl/R500 to construct the Mgii REW-profile. The details of the bins and the measurements are summarized in supplementary Table S1. The REW-profiles for the mean/median Mgii absorption are shown in Fig. 3. A decrease in the Mgii REW with increasing ρcl and ρcl/R500 is evident from the figure.

4. DISCUSSION AND CONCLUSION

We detect 7σ significant Mgii and marginal Feii absorption in the mean stacks arising from the CCM of z ≈ 0.5 clusters with a median mass of ≈ 10^{14.2} M_{⊙}. Our results show that cluster outskirts (1–5 R_{500}) are enriched with heavy elements. The mean and median Mgii REW measured from our stacks are consistent with the values inferred by Anand et al. (2022, see their Eqn. 5) at the median ρcl/R500 (= 3.6) within 2σ.

The prevalence of metal-rich, cool/warm-hot gas in the outskirts is also seen in theoretical studies of Virgo-like and Coma-like clusters (see Emerick et al. 2015;
Table 1. Summary of the measurements performed on the mean and median stacks.

| Sample          | $N_{\text{pairs}}$ | $z_{\text{cl}}$ | $M_{500}$ ($10^{14} M_\odot$) | $R_{500}$ (Mpc) | $\rho_{cl}$ (Mpc) | $\rho_{cl}/R_{500}$ | REW(Mg II) in Å | Mean/Median | ... |
|-----------------|--------------------|-----------------|--------------------------------|-----------------|-------------------|-------------------|-----------------|-------------|-----|
| Full            | 79485              | 0.54(0.46–0.62) | 1.47(1.10–2.31)                | 0.65(0.59–0.75) | 2.40(1.46–3.16) | 3.6(2.2–4.6)     | 0.034±0.005 | 0.010±0.003 | ... |
| Ex-CGM          | 63210              | 0.54(0.47–0.63) | 1.49(1.11–2.34)                | 0.65(0.59–0.76) | 2.42(1.48–3.17) | 3.6(2.2–4.6)     | 0.031±0.005 | 0.010±0.003 | ... |

Notes – (1) Sample name used in stacking (see Section 3). (2) Number of quasar-cluster pairs for a given sample. (3), (4), (5), (6), and (7) median values of cluster redshift, $M_{500}$, $R_{500}$, $\rho_{cl}$, and $\rho_{cl}/R_{500}$ respectively. The values in the parenthesis for the parameters listed from (3) – (7) indicate the 16 and 84 percentiles of the parameter distribution. (8) & (9) REWs of Mg II line measured between 2785–2815 Å from the mean and median stack spectra, respectively. (10) & (11) Column density estimated using the Mg II REWs in (8) and (9), respectively, assuming lines are in the linear part of the COG. (12) & (13) REWs of Fe II line measured between 2589–2611 Å from the mean and median stack profiles, respectively. (14) & (15) Same as (10) & (11) but for Fe II line. (16) & (17) Line widths calculated from three-component Gaussian fits to the Fe II A2600 and Mg II A2796,2803 lines for the mean and median stacked spectra, respectively. We tied the line widths of the Mg II and Fe II lines. (18) & (19) Line centroids obtained from the fitting for the mean and median stack spectra, respectively.

Figure 3. **Left:** REW of Mg II obtained from the mean (bottom) and median (top) stacked spectra versus impact parameter ($\rho_{cl}$). The REWs measured for the full sample are shown in black solid circles. The measurements for the “Ex-CGM” subsample, i.e., after excluding the quasar-cluster pairs that can have significant contribution from the CGM of galaxies in the cluster outskirts near the quasar sightlines (see Section 4), are shown in open red circles. The error bars along the y-axis indicate the 1σ range obtained from combining the statistical uncertainty from 200 bootstrap realizations and pseudo-continuum placement error , while the error bars along the x-axis represent the 68 percentile range for $\rho_{cl}$ bin. The right y-axes show the Mg II column density corresponding to the REW on the left for the linear part of the COG. **Right:** Same as the left panel but for $\rho_{cl}/R_{500}$.
These authors suggested that the cool gas in the outskirts are associated with the infall of pristine gas from the IGM and/or with early-stage stripping of the CGM of infalling galaxies. As a consequence, the gas in the outskirts shows a wide range in metallicity (see Fig. 5 of Butsky et al. 2019). The existence of metal-rich gas in the cluster outskirts, as we observed here, can also be explained by a uniform early metal enrichment scenario where deposition and mixing of heavy elements occurred well before the cluster formation when the star formation and AGN activities were on their peaks (i.e., $z \gtrsim 2$; see Simionescu et al. 2015; Urban et al. 2017). Alternatively, theoretical models of clusters predict that cool gas ($\sim 10^4$ K) can condense out of the hot ICM plasma ($\sim 10^7$ K) due to thermal instability when the cooling time scale ($t_{\text{cool}}$) reaches 10 times below the gravitational free-fall timescale ($t_{\text{ff}}$, e.g., McCourt et al. 2012; Sharma et al. 2012; Voit et al. 2017). However, such a process is not important at distances $\gtrsim$ 100 kpc from cluster centres owing to the large $t_{\text{cool}}/t_{\text{ff}}$ ratio ($\gtrsim 10$, e.g., Hogan et al. 2017) due to the rapidly decreasing density of the hot gas with distance. We recall that the regions we probed here are even further away from cluster centres.

We find a decreasing trend between Mg ii REW and $\rho_{\text{cl}}$ and $\rho_{\text{cl}}/R_{500}$, likely due to the lower density, metallicity, and covering fraction of cool gas at large radii (Emerick et al. 2015; Butsky et al. 2019). A similar declining trend is well-known in the CGM literature for decades (e.g., Lanzetta & Bowen 1990; Chen et al. 2010; Nielsen et al. 2018; Dutta et al. 2021). Adopting the relation presented in Dutta et al. (2021), we obtained galactocentric distances of 200 – 300 kpc for the Mg ii REW we measured from the stacked profiles, provided that the absorption signal is dominated by the CGM of galaxies in the outskirts. To quantify the possible contribution from the CGM of galaxies in the outskirts, we searched for galaxies in the SDSS using CasJobs.6

We limited our search to the galaxies with “photoErrorClass” flags of −1, 1, 2, and 3 with reliable photometric measurements. These galaxies have typical uncertainty of $\approx 0.03$ in the photometric redshifts 7 (Beck et al. 2016). We excluded 16,275 pairs from our analysis for which at least one galaxy is detected within 300 kpc radius centred on the background quasar with a photometric or spectroscopic redshift consistent with the cluster redshift within $\pm 6000$ km s$^{-1}$.8 The measurements obtained for this sub-sample after excluding the possible CGM contribution (“Ex-CGM”) are summarized in Table 1.9 The mean/median Mg ii and Fe ii REWs for the “Ex-CGM” sub-sample are consistent within 1σ with the full sample. Moreover, the “Ex-CGM” sub-sample shows trends similar to the full sample (see Fig. 3). We, thus, conclude that the absorption is not dominated by the CGM of bright ($\sim L_*$) galaxies in the outskirts near the quasar sightlines. However, we cannot rule out the possibility of contribution from the CGM of low-mass/faint galaxies. In passing, we note that the stacked spectra for the 16, 275 quasar-cluster pairs with possible CGM contributions exhibit a stronger Mg ii absorption with mean and median REWs of 0.053±0.007 Å and 0.020±0.003 Å, respectively.

We run grids of photoionization models using CLOUDY (v17.02; Ferland et al. 2017) with metallicity ($\log_{10} Z$), neutral hydrogen column density ($\log_{10} N$(H i)/cm$^{-2}$), and density ($\log_{10} n_{\text{H}}$/cm$^{-3}$) ranging from $-2.0 - 0.0$, $14.0 - 18.0$, and $-3 - 0$, respectively, in steps of 0.5 dex. We assumed that the absorbing medium has solar relative abundance, and is subjected to the extragalactic UV background radiation at $z = 0.5$ obtained from Haardt & Madau (2012). These models suggest a moderate density of $n_{\text{H}} > 10^{-2.0}$ cm$^{-3}$ to reproduce the observed mean $N$(Mg ii)/$N$(Fe ii) ratio, for the whole range of $N$(H i) and metallicity explored. Moreover, the metallicity required to match the observed mean Mg ii and Fe ii column densities is $\log_{10} Z \gtrsim -1.5$, provided $\log_{10} N$(H i)/cm$^{-2} < 17.2$ (sub-LLS) and $\log_{10} n_{\text{H}}$/cm$^{-3} > -2.0$. The density and metallicity constraints obtained from these simple ionization models favor an origin similar to circumgalactic gas as opposed to pristine filamentary accretion for the absorption signal detected here. However, the strength of the Mg ii absorption for the Ex-CGM sample is consistent with the full sample, implying that the signal is not dominated by the gas locked in the CGM of bright galaxies near the background quasars. These two facts suggest that the Mg ii absorption likely to arise from stripped gas, and that stripping can be important at such large distances ($\rho_{\text{cl}} \approx 2.4$ Mpc). The simulations of Butsky et al. (2019) also showed that CGM stripping is relevant for galaxies as far as 4$R_{200}$. Similarly, based on the little correlation between the Mg ii absorbers and

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6 [https://skyserver.sdss.org/casjobs/](https://skyserver.sdss.org/casjobs/)

7 This corresponds to a velocity of $\approx 6000$ km s$^{-1}$ at the median cluster redshift of 0.5.

8 We have identified nearly 20, 000 ($\sim L_*$) galaxies satisfying these conditions with median $r$-band apparent and absolute magnitudes of $\approx 21.6$ and $\approx -21.4$, respectively.

9 The mean and median composite spectra for this sample are shown in supplementary Fig. S1.
properties of their nearest galaxies within $R_{200}$ of clusters and the fact that the mean absorber—nearest galaxy separation is larger (>200 kpc) than the typical size of star-forming disk of the galaxy, Anand et al. (2022) argued that the cool gas in the outskirts can in part arise from stripping.

Using the empirical relationship between $\text{REW}(\text{Mg} \, II)$ and $N$(H I) obtained by Lan & Fukugita (2017), we obtained $N$(H I) $\approx 10^{16.8}$ cm$^{-2}$ for the mean $\text{REW}(\text{Mg} \, II)$ of 0.034 A, suggesting a sub-LLS environment for the absorbing gas. Such high H I column densities are consistent with the observations of Muzahid et al. (2017) but rarely observed in the outskirts of Virgo/Coma clusters (see Fig. 3 of Muzahid et al. 2017) and in hydrodynamical simulations (see e.g., Emerick et al. 2015). It may be possible that the empirical relation is not valid for such low Mg II $\text{REW}$. Dedicated UV absorption line programs using $HST$ are essential to map the distribution of neutral gas and to probe the multiphase structure of cluster outskirts.

In conclusion, using a large sample of quasar-cluster pairs, we report strong Mg II and marginal Fe II absorption in the composite spectra of quasars arising from the CCM of $z \approx 0.5$ clusters with a median mass of $\approx 10^{14.2} \, M_\odot$. This is the first statistical detection of metal-enriched, cool gas in the outskirts of galaxy clusters. We discussed the possibilities, such as filamentary accretion from the IGM, uniform early metal enrichment, ICM cooling, stripped of galactic materials, and gas locked in the CGM, that could give rise to the detected absorption. We showed that the CGM of bright galaxies ($\approx L_*$) in the outskirts does not dominate the signal. The chemical and physical conditions inferred from simple photoionization models, however, suggest that the absorption is arising from gas with moderate density and metallicity which are typical of the CGM. We therefore speculate that the absorption stems from stripped of galactic materials and that stripping may be important at large clustocentric distances ($\approx 3 - 4R_{500}$) as seen in some recent cosmological hydrodynamical simulations. But the possibility of contribution from the CGM of low-mass/faint galaxies to the detected absorption signal cannot be ruled out. Future large galaxy surveys with deeper photometric and/or spectroscopic completeness can shed light on this. We plan to determine the covering fraction of Mg II in the cluster outskirts and investigate environmental effects on the CGM using the $\approx 20,000$ galaxies in the outskirts identified within 300 kpc of the quasar sightlines in the future.

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Figure A1. An illustration of our continuum-fitting algorithm. First, we normalize the original spectrum (black, a) with the default SDSS PCA continuum (green, a). After that, we perform an iterative boxed-sigma clipping with asymmetric levels on the upper and lower sides of the normalized continuum. The yellow data points, marked as outliers, in the panel (b) indicate the location of possible absorption features that are clipped by our clipping algorithm. The blue scatter points in the panel (b) show the sigma-clipped spectrum. Clipping is performed at 50 and 2 upper and lower sigma levels, respectively, after dividing the spectrum in 10 boxes of 90 Å width. We smooth these sigma-clipped data points using 51 pixels to minimize residual absorption (red, b). We then linearly interpolate the red data points in (b) to generate a smooth model (cyan, c). Finally, we fit a spline (of 70 knots in this case) over this interpolated model resulting in the final continuum fit (magenta, d). Note that our adopted continuum in magenta is significantly improved compared to the default SDSS continuum shown in green, particularly near the strong absorption at ≈ 4300 Å.

APPENDIX
Figure A2. Examples of SDSS spectra (in black), default SDSS continua (in green) and our improved continua (in magenta). The spectral regions correspond to ±30,000 km s\(^{-1}\) around the cluster redshifts. The upper and lower sigma levels (Sig\(_{u}/l\)), the number of boxes (Nbox) within which each spectrum is divided, the number of pixels used for smoothing (Smooth) and the number of knots (Knot) used for the spline fitting are given on the top right corner of each panel. At the centre of each panel, the dashed line corresponds to the cluster’s Mg\(_{II}\) doublet location. Our new algorithm significantly improved our adopted continuum in all three cases compared to the SDSS PCA continuum.

Supplementary Material (online-only)

S1. STACKS FOR DIFFERENT SUB-SAMPLES

In Fig. S1, we show the mean and median stack spectra of the “Ex-CGM” sample excluding the 16, 275 quasar–cluster pairs for which we found at least one galaxy within a radius of 300 kpc around the background quasars and having a photometric or spectroscopic redshift consistent with the cluster redshift within ±6000 km s\(^{-1}\).

In Fig. S2, we present the mean (bottom) and median (top) stacked spectra for three bins of cluster redshift (z\(_{cl}\)) ensuring each bin contains almost an equal number of quasar–cluster pairs. The details of these bins are given in Table S1.

In Fig. S3, we present the mean (bottom) and median (top) stack spectra for three bins of \(M_{500}\) ensuring each bin contains almost an equal number of quasar–cluster pairs. The details of these bins are given in Table S1.
Figure S1. Top: Median composite spectrum of the background quasars at the rest-frame of the clusters for the “Ex-CGM” sample (excluding the 16,275 quasar-cluster pairs where the quasars may be probing the CGM of galaxies in the outskirts). The 1σ errorbars on flux are estimated from 200 bootstrap samples and are shown in grey. The solid green curve shows the best-fit pseudo continuum. The best-fit Mg II and Fe II absorption profiles are shown in magenta curves. The line centroids are shown by the arrows. The four dashed horizontal lines two each around Fe II and Mg II corresponds to [2589, 2611] Å and [2784, 2815] Å regions used for rest-frame equivalent width measurements. Bottom: same as the top panel but for the mean composite spectrum.

In Fig. S4, we present the mean (bottom) and median (top) stack spectra for three bins of $\rho_{\text{cl}}$ ensuring each bin contains almost an equal number of quasar–cluster pairs. The details of theses bins are given in Table S1.

In Fig. S5, we present the mean (bottom) and median (top) stack spectra for three bins of $\rho_{\text{cl}}/R_{500}$ ensuring each bin contains almost an equal number of quasar–cluster pairs. The details of theses bins are given in Table S1.

In Table S1, we summarize the bin details and their corresponding stacked results for our various sub-samples that are binned in $z_{\text{cl}}$, $M_{500}$, $\rho_{\text{cl}}$, and $\rho_{\text{cl}}/R_{500}$.
Figure S2. Same as Fig. S1 but for three different bins of cluster redshift.
Figure S3. Same as Fig. S1 but for three different bins of $M_{500}$. 
Figure S4. Same as Fig. S1 but for three different bins of $\rho_{cl}$. 
Figure S5. Same as Fig. S1 but for three different bins of $\rho_{\text{cl}}/r_{500}$. 
Table S1. Summary of the measurements for the subsamples.

| Bin | $N_{pairs}$ | $z_{cl}$ | $REW$(Mg$\text{\textsc{ii}}$) in Å | $\log_{10} N$(Mg$\text{\textsc{ii}}$)/cm$^{-2}$ | $REW$(Fe$\text{\textsc{ii}}$) in Å | $\sigma_{\text{V}}$ (km s$^{-1}$) | $\sigma_{\lambda}$ (Å) | $\chi_{\nu}$ (km s$^{-1}$) | $V_{\nu}$ (km s$^{-1}$) |
|-----|-------------|----------|-------------------------------|--------------------------------|-------------------------------|-------------------|------------------|------------------|------------------|
|     |             |          | Mean (1) | Median (2) | Mean (3) | Median (4) | Mean (5) | Median (6) | Mean (7) | Median (8) |
| 0.49<z<0.57 | 26416 | 0.460 | 0.032±0.009 | 0.012±0.006 | 11.71±0.41 | 11.29±0.42 | 0.009±0.012 | 0.014±0.005 | 11.82±0.44 | 11.99±0.43 |
| 0.53<z<0.57 | 26516 | 0.530 | 0.030±0.008 | 0.011±0.004 | 11.67±0.41 | 11.22±0.42 | 0.021±0.008 | 0.011±0.005 | 12.16±0.42 | 11.88±0.42 |
| 0.67<z<0.72 | 26523 | 0.670 | 0.045±0.007 | 0.010±0.004 | 11.85±0.40 | 11.20±0.42 | 0.011±0.006 | 0.006±0.004 | 11.90±0.42 | 11.60±0.43 |

Notes: (1) Bin range. (2) Number of quasar-cluster pairs in that bin. (3) Median value of the binning parameter in that bin. The upper and lower values in (3) indicate the 16 and 84 percentiles of the parameter distribution. (4) & (5) Rest-frame EWs of Mg $\text{\textsc{ii}}$ line measured between 2785–2815 Å from the mean and median stack spectra, respectively. (6) & (7) Column density estimated using the Mg$\text{\textsc{ii}}$ $REW$s in (4) & (5), respectively, assuming lines are in the linear part of the curve-of-growth. (8) & (9) Rest-frame EWs of Fe $\text{\textsc{ii}}$ line measured between 2598–2611 Å from the mean and median stack profiles, respectively. (10) & (11) Same as (6) & (7) but for Fe $\text{\textsc{ii}}$ line. (12) & (13) Line widths calculated from three-component Gaussian fits to the Fe $\lambda\lambda$2600 and Mg $\lambda\lambda$2796,2803 lines for the mean and median stacks, respectively. We tied the line widths of the Mg $\text{\textsc{ii}}$ and Fe $\text{\textsc{ii}}$ lines. (14) & (15) Line centroids obtained from the fitting for the mean and median stack spectra, respectively.