CONVERSES ON COOL GAS IN RICH CLUSTERS OF GALAXIES

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ABSTRACT

Cool gas should be present in galaxy clusters due to stripping of galactic gas, in-fall onto the cluster, and from cooling flows. We have searched for this gas through metal resonance absorption lines from low-ionization gas toward six background quasars. Both cooling-flow and non–cooling-flow clusters were observed, with lines of sight ranging from the inner to outer parts of the cluster (0.32 Mpc ≤ rproj ≤ 1.40 Mpc). The HST Faint Object Spectrograph observations failed to detect Fe ii or Mg ii absorption at the cluster redshift, with 1σ upper limits on the ion column densities of N ≤ 10^{12–13} cm^{-2}. From existing X-ray data, we estimate that ram-pressure stripping of galactic gas by the intracluster medium should produce cool gas along these sight lines. The failure to detect absorption lines implies that any gas stripped in such a way has a low covering fraction, possibly due to a short lifetime in this low-ionization state.

Subject headings: galaxies: clusters: general — quasars: absorption lines

On-line material: machine-readable table

1. INTRODUCTION

Rich clusters of galaxies, such as the Abell clusters, are filled with ~10^{14} M⊙ of hot (T ~ 10^7) X-ray emitting gas (see, e.g., Fabian, Nulsen, & Canizares 1991). The density of this gas is largest in the central region (n_e ≈ 0.001–0.1 cm^{-3}) and decreases with radius, where it becomes undetectable to X-ray instruments when n_e < 10^{-4} cm^{-3} (typically at radii of 1–3 Mpc; H_0 = 50 km s^{-1} Mpc^{-1} throughout). Although studies of cluster gas have focused on the hot medium, three important processes can produce cool gas (T ~ 10^{3–4} K) in rich clusters of galaxies: stripping of galactic gas by the hot ambient medium; in-fall of cool gas into the cluster; and the radiative cooling of the hot gas in the cluster core (cooling flows).

The stripping of galactic gas is expected to be the main process by which the cluster gas becomes enriched, so it is central to interpreting cluster metallicities. The rate at which gas is removed from the ensemble of galaxies is ~100 M⊙ yr^{-1} (Soker, Bregman, & Sarazin 1991). This gas should be near solar metallicity, and the stripping should occur in the inner 1 Mpc of the cluster, where the ambient medium is densest (Gaetz, Salpeter, & Shaviv 1987). The in-fall of gas onto clusters occurs at the outer regions (3 Mpc radius), it will involve low-metallicity material, and the in-fall rate is expected to be ~10^{3–4} M⊙ yr^{-1}. This in-fall of gas is a prime growth mechanism for clusters. Finally, in the central 100 kpc, clusters with cooling flows are believed to deposit cooled gas of approximately 1/3 solar metallicity at rates in excess of ~100 M⊙ yr^{-1}. Each of these mechanisms is distinct both in the spatial distribution for the absorption and in the metallicity of the gas. This paper is the first in an endeavor by us to study this cooled gas through the presence of absorption lines.

There have been studies at a variety of wavebands in an effort to detect cool gas. Direct detection of H i in absorp-

tion and emission have met with some success, although large quantities of gas are not discovered, and CO emission remains undetected (McNamara, Bregman, & O’Connell 1990; McNamara & Jaffe 1994; O’Dea, Baum, & Gallagher 1994a; O’Dea et al. 1994b; O’Dea, Gallagher, & Baum 1995; O’Dea, Payne, & Kocevski 1998). Indirect evidence for cool gas has been obtained by far-infrared studies that are sensitive to thermal reemission from dust, where weak emission is seen in a minority of galaxy clusters (Maoz 1995; Cox, Bregman, & Schombert 1995; Stickel et al. 1998).

Large amounts of cooled gas (10^{12} M⊙) are inferred from the excess soft X-ray absorption toward the central regions (within r < 0.5 Mpc) of cooling-flow clusters (White et al. 1991; Allen et al. 1993; Fabian et al. 1994; Fukazawa et al. 1994), although this result has been questioned (Arabadjis & Bregman 1999).

Cooled material is detectable through UV and optical absorption line studies against background point sources. In a recent study, Koekemoer et al. (1998) searched for absorption against a quasar associated with the central galaxy of Abell 1030. No lines attributable to the ICM were detected, and they obtain 1σ upper limits on the column density for a number of species, including H i (N < 10^{12.4} cm^{-2}), Mg ii (N < 10^{11.5} cm^{-2}), and Fe ii (N < 10^{12.0} cm^{-2}). In another study, toward NGC 1275 in Perseus (Johnstone & Fabian 1995), there is a dip in the middle of the Lyα emission line at the velocity of the 21 cm H i absorption feature, which may be interpreted as Lyα absorption with an equivalent width in the 1–5 Å range. However, the authors interpret the Lyα emission line as being double but without absorption.

This illustrates one of the difficulties of searching for cool ICM gas against an AGN at the same redshift; namely, it is difficult to separate possible absorption features from structure in the AGN emission lines. Additionally, unless sufficient velocity resolution is achieved to determine the
kinematic structure, it can be difficult to distinguish cluster absorption features from AGN absorption features. Finally, a failure to detect absorption might be due to the strong photoionizing influence of the AGN on the cool gas (although this can be ruled out if the gas is not detected in optical line emission around the AGN). While these three potential problems can be overcome in certain situations, all three are completely avoided by searching for cool ICM gas through absorption against background AGNs which are unrelated to the cluster. This technique has the desirable feature that the cluster and background source are well separated in velocity space, allowing clean identification of spectral features from each. In addition, for sight lines projected close to the cluster center, the path length covers most of the cluster, thus increasing the likelihood of detection.

We have obtained near-UV spectra of five background quasars behind different clusters, supplemented by an additional quasar spectrum from the *HST* archive. With these six independent lines of sight at various distances from the cluster cores, we have searched for low-ionization metal resonance lines.

### 2. DESCRIPTION OF THE DATA

#### 2.1. Target Selection

Most of the background AGNs were identified by us as part of a program to find continuum point sources positioned behind galaxies and clusters of galaxies (Knezeck & Bregman 1998). A cross-correlation of the Abell (1958) catalog with AGN catalogs (e.g., Hewitt & Burbidge 1993) turns up only a few positive results, thus we developed our own search technique to identify a larger sample of background sources. We started with a sample of 207 Abell clusters created by White, Jones, & Forman (1997) from the *Einstein Observatory* archive. This sample is not flux-limited; however, it provides a fairly representative collection of rich clusters due to its size alone. After limiting the sample to clusters with $\delta \geq -15^\circ$, we determined that nearly 60 of them had accessible archived *ROSAT* X-ray images. We then searched these images for point sources falling within one-half of the cluster radius, as given by Abell (1958). Any such point source not found in the Guide Star Catalog or standard optical and radio catalogs could be a background AGN. We obtained optical spectrophotometry of the sources with the MDM 2.4 m telescope, and when AGNs were confirmed through their emission line spectra, we determined their redshifts, fluxes, and spectral shapes.

The confirmed AGNs, along with several from the cross-correlation of the Abell and AGN catalogs, were screened by brightness, redshift, reddening, and projected distance from the cluster center, and the best targets were chosen for observation with the *Hubble Space Telescope* (*HST*). In particular, to allow for unambiguous detection of the Mg $\text{ii}$ 2800 doublet, we limited the redshift to $z < 1.3$. At redshifts greater than this, the Ly$\alpha$ forest is shifted redward of the Mg $\text{ii}$ doublet, which could cause false detections of Mg $\text{ii}$. (This is a problem for one of the observations, taken from the archive, as the background AGN has $z = 1.36$.)

The first sample of six AGNs observed with *HST* have all been identified as quasars. They are listed in Table 1. The clusters through which these sight lines pass are representative of rich clusters as a whole, as our selection of AGNs samples a range of projected radii and X-ray properties. Two of the AGN sight lines lie within 0.5 Mpc of the cluster center, three lie between 0.8–1.0 Mpc, and one lies at 1.4 Mpc. It should be noted that none of these sight lines fall within the cluster core radius (typically 200–400 kpc) or within the radius of a typical cooling flow (100 kpc). Therefore, our results apply only to the mid-ranges of clusters, where we expect galactic ram-pressure stripping to be the dominant cool gas production mechanism. With regards to the X-ray properties, one of the clusters, Abell 1795, exhibits a very large cooling rate, while Abell 754 has a more modest flow. Two of the clusters, Abell 21 and Coma (Abell 1656), show no evidence of cooling flows. The remaining two, Abell 151 and Abell 1267, do not have public X-ray data, although they are nearby and should be bright. Finally, our sample is unbiased by the selection of AGNs, since these background sources are completely uncorrelated to the clusters themselves.

#### 2.2. Observations and Data Reduction

The data for this project were obtained with the Faint Object Spectrograph (FOS) on board *HST*. Each spectrum was taken through the 0.86 circular aperture using the G270H grating and Red Digicon detector. In this configuration, the spectrum covers the 2222–3277 Å range, and the expected FOS instrumental line width (FWHM) is 2.04 Å, which produces a spectral resolution of 219 km s$^{-1}$ at 2800 Å.

### TABLE 1

**Summary of Observations and Target Characteristics**

| QSO     | $z_{qso}$ | $t_{exp}$ (s) | Date Obs. | Cluster | $z_{cluster}$ | $r_{proj}$ (Mpc) | $\sigma$ (km s$^{-1}$) | $M_c$ (M$_{\odot}$ yr$^{-1}$) |
|---------|-----------|---------------|-----------|---------|---------------|-------------------|---------------------|------------------|
| 0020 + 287 ....... | 0.51 | 7820 | 1996 Nov 17 | Abell 21 | 0.0946 | 0.50 | 621 | 0 |
| 0107−156 ....... | 0.86 | 3970 | 1996 Jul 27 | Abell 151 | 0.0533 | 0.92 | 669 | ... |
| 0909−095 ....... | 0.63 | 8740 | 1997 Feb 11 | Abell 754 | 0.0542 | 0.80 | 931 | 24 |
| 1124 + 271 ....... | 0.378 | 4050 | 1996 Nov 28 | Abell 1267 | 0.0329 | 0.32 | 190 | ... |
| 1258 + 285 ....... | 1.36 | 2100 | 1995 Apr 5 | Coma | 0.0231 | 0.81 | 1008 | 0 |
| 1348 + 263 ....... | 0.59 | 6410 | 1997 Jan 22 | Abell 1795 | 0.0631 | 1.40 | 920 | 295 |

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a Redshift for QSO 1258+285 is from Wegner & Swanson 1990, all other QSO redshifts are from Knezeck & Bregman 1998.
b Cluster redshifts and velocity dispersions are from Struble & Rood 1999.
c $r_{proj}$ is the projected distance of the QSO line of sight from the cluster center.
d $M_c$ is the cooling rate, taken from a catalog discussed by Arnaud 1988. It is zero for non–cooling-flow clusters.
e The spectra for this quasar were taken from the *HST* Data Archive.
The observations are summarized in Table 1, which lists the date and exposure time for each observation, as well as characteristics of each quasar and cluster. Five of the observations were obtained for this program. The sixth, QSO 1258+285 behind the Coma cluster, was obtained from the HST Data Archive to increase our sample. Additional GHRS spectra in the far-UV were also retrieved but were found to be of poor quality for this project.

Each data set was recalibrated with the CALFOS routine in the IRAF/STSDAS package, using the best reference files available. This produced a substantial improvement (about a factor of 1.5) in the signal-to-noise ratio over the initial pipeline processing. The calibrated spectra along with the propagated photon counting errors are shown in Figure 1; important quasar emission lines are marked.

3. ANALYSIS
3.1. Absorption Line Searching and Identification

The identification of absorption lines and measurement of their strengths were performed using the HST Quasar Absorption Line Key Project software (Schneider et al. 1993). First, a quasar “continuum” was fitted to each spectrum with a series of spline curves; this fit included the quasar emission lines to allow detection of absorption lines superimposed on these features. Each spectrum and associated error array was then normalized to unity. The line-searching software takes as input parameters the maximum Gaussian width (FWHM), detection threshold (defined in terms of the significance level of the measured equivalent width), and the instrumental PSF characteristics. The software performs two types of fitting to the input spectrum: PSF fitting for unresolved lines; and Gaussian fitting for resolved lines, applying multiple Gaussians in the case of blended features. (A detailed description of the line-searching algorithm is provided by Schneider et al. 1993.) For our analysis, a detection threshold of 3 \( \sigma \) was used. Additionally, we constrained the FWHM of an absorption line to lie between the instrumental limit and that corresponding to a velocity dispersion of 1200 km s\(^{-1}\). All of our clusters have measured galaxy velocity dispersions, ranging from 190 km s\(^{-1}\) for Abell 1267 to 1008 km s\(^{-1}\) for Coma (Struble & Rood 1999).

Several absorption lines were detected in each spectrum, and these are listed in Table 2 under the appropriate quasar.

![Calibrated HST/FOS spectra of six quasars projected behind clusters. Axes are flux in units of 10\(^{-15}\) ergs s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) vs. wavelength in Å. The upper line traces the quasar “continuum” fit, while the lower line shows the 3 \( \sigma \) error spectrum which is propagated through the HST reduction pipeline along with the science data. Quasar emission lines are identified, and strong Galactic absorption lines are denoted with dotted lines. Tick marks denote special absorption features discussed in the text. Regions marked with a bold line are locations we expect to see absorption from Fe II or Mg II in the cluster.](image-url)
name. The table lists the observed wavelength (see discussion below), measured equivalent width, line width (or instrumental limit if the line is unresolved), our identification, and the velocity (for Galactic features) or redshift (for extragalactic features) of the absorber. The strong Galactic lines of Fe ii \((\lambda 2344, \lambda 2374, \lambda 2382, \lambda 2586, \text{and} \lambda 2600)\), Mg ii \((\lambda 2796, 2803)\), and Mg i \((\lambda 2853)\) appear in every spectrum, with line strengths ranging from 0.2 Å for the Mg i line to about 1.0 Å for the stronger line of the Mg ii doublet (Fig. 1; all wavelengths are in vacuum).

Analysis of the Galactic features sheds some light on the quality of the wavelength calibration. The wavelength zero point of FOS was not constant between observations, but varied as a result of nonrepeatability of the filter/grating wheel position, in addition to other effects. Since contemporaneous wavelength calibration data were not taken with any of the object spectra, the wavelength zero point could be displaced by as much as 250 km s\(^{-1}\) (Keyes 1998). Indeed, the line centers of the Galactic lines are shifted from rest by as much as 2.0 Å \((\pm 225 \text{ km s}^{-1})\) in our spectra. Since it is impossible to separate true Galactic motion from errors in the wavelength zero point, we have adopted the convention of the HST key project team and have shifted each spectrum so that the Milky Way lines are at rest, using the strong Fe ii and Mg ii lines as reference. All data and figures reported in this paper reflect this adjustment.

In addition to the Galactic lines, several other features have been identified in the spectra and are described in the following section. No sets of lines within ±3000 km s\(^{-1}\) of the cluster redshift were identified for any of the clusters. The spectra in Figure 1 show the regions in which we would expect to see the Mg ii or Fe ii absorption produced by cool cluster gas.

To detect fainter absorption features, we searched each spectrum using a detection threshold of 1.5 \(\sigma\). Detected lines falling within the expected regions were compared in velocity and line strength to see if they were plausible components of the same species. No satisfactory matches were made.

3.2. Detected Absorption Systems

We detect absorption by several systems which are unrelated to the intervening Abell clusters or to the Galaxy. While a full analysis of these phenomena is outside the scope of this paper, we summarize our findings here to provide a foundation for future work.

**QSO 0107–156.**—We observe a \(W_{\lambda} \approx 1.0 \text{ Å} \) absorption line at 2244.8 Å, superimposed on the quasar Ly\(\alpha\) emission line. This could be due to an H i absorber in the AGN itself, in which case the cloud would be outflowing at \(-1630 \text{ km s}^{-1}\) relative to the quasar. This scenario seems somewhat unlikely, given that the line width is quite narrow (290 ± 20
List of Detected Absorption Lines

| $\lambda_{\text{det}}$ (Å) $^a$ | $W_{\lambda}$ (Å) $^b$ | FWHM (Å) $^b$ | ID$^c$ | $v$ or $z^d$ |
|-------------------------------|-----------------|---------------|------|------------|
| 2344.79 ± 0.07………… | 0.98 ± 0.06 | 2.14 ± 0.16 | H i 1215.67 (QSO) | 0.847 |
| 2257.28 ± 0.28………… | 0.19 ± 0.04 | ≤2.02 | …… | …… |
| 2263.05 ± 0.47………… | 0.32 ± 0.08 | 3.99 ± 1.14 | …… | …… |
| 2268.67 ± 0.26………… | 0.25 ± 0.05 | ≤2.02 | …… | …… |
| 2344.14 ± 0.42………… | 0.53 ± 0.13 | 3.62 ± 1.02 | Fe ii 2344.21 (MW) | 20 ± 94 |
| 2382.83 ± 0.17………… | 0.95 ± 0.12 | 2.83 ± 0.42 | Fe ii 2382.76 (MW) | 20 ± 21 |
| 2397.53 ± 0.11………… | 0.94 ± 0.10 | 2.16 ± 0.27 | C iv 1548.20 | 0.549 |
| 2402.00 ± 0.15………… | 0.62 ± 0.08 | ≤2.02 | C iv 1550.77 | 0.549 |
| 2577.41 ± 0.34………… | 0.24 ± 0.07 | ≤2.04 | Mn ii 2576.88 (MW) | 62 ± 40 |
| 2600.01 ± 0.22………… | 1.14 ± 0.11 | 4.63 ± 0.55 | Fe ii 2600.17 (MW) | 18 ± 25 |
| 2607.00 ± 0.43………… | 0.36 ± 0.10 | 3.29 ± 1.04 | Mn ii 2606.46 (MW) | 62 ± 49 |
| 2778.91 ± 0.37………… | 0.23 ± 0.07 | ≤2.04 | …… | …… |
| 2796.35 ± 0.14………… | 0.95 ± 0.10 | 2.88 ± 0.35 | Mg ii 2796.35 (MW) | ±1 ± 15 |
| 2803.60 ± 0.20………… | 0.89 ± 0.11 | 3.43 ± 0.48 | Mg ii 2803.53 (MW) | ±7 ± 21 |
| 2884.86 ± 0.29………… | 0.26 ± 0.06 | ≤2.04 | …… | …… |
| 3190.84 ± 0.36………… | 0.25 ± 0.07 | ≤2.04 | …… | …… |
| QSO 0909–095: $z_{\text{QSO}} = 0.63$, $z_{\text{clust}} = 0.0542$ | | | | |
| 2286.25 ± 0.37………… | 0.39 ± 0.11 | 2.60 ± 0.89 | …… | …… |
| 2314.85 ± 0.37………… | 0.30 ± 0.09 | ≤2.02 | …… | …… |
| QSO 0112+271: $z_{\text{QSO}} = 0.378$, $z_{\text{clust}} = 0.0329$ | | | | |
| 2252.05 ± 0.62………… | 0.35 ± 0.10 | 4.45 ± 1.49 | …… | …… |

QSO 0020 + 287: $z_{\text{QSO}} = 0.51$, $z_{\text{clust}} = 0.0946$
TABLE 2—Continued

| \( \lambda_{\text{phot}} \) (Å) | \( W_\lambda \) (Å) | FWHM (Å) | ID | \( \nu \) or \( z_{\text{dust}} \) |
|-----------------|------------|---------|-----|----------------|
| 2344.48 ± 0.15 | 0.62 ± 0.09 | \( \leq 2.04 \) | Mn II 2803.53 (MW) | +35 ± 19 |
| 2375.97 ± 0.76 | 0.82 ± 0.18 | 7.45 ± 1.94 | Fe II 2586.65 (MW) | +191 ± 96 |
| 2382.71 ± 0.09 | 0.83 ± 0.07 | \( \leq 2.04 \) | Fe II 2374.46 (MW) | +6 ± 11 |
| 2418.64 ± 0.39 | 0.20 ± 0.06 | \( \leq 2.04 \) | ... | ...
| 2432.60 ± 0.56 | 0.39 ± 0.12 | 3.85 ± 1.32 | ... | ... |
km s\(^{-1}\) FWHM in the rest frame) and one would expect to see a broader range of velocities in such an outflow. It is conceivable that the absorber is a foreground object, possibly not related to the AGN at all.

This spectrum contains two additional absorption lines that are more difficult to identify: \(W_\lambda = 0.94\ \text{Å} \) at 2397.5 Å and \(W_\lambda = 0.63\ \text{Å} \) at 2402.0 Å. In the rest frame of the cluster, these lines would fall at 2277.7 and 2282.0 Å, respectively; in the rest frame of the quasar, they would be 1288.3 and 1290.7 Å. There are no known resonance lines at these wavelengths. If this absorption were due to intervening material, e.g., from Fe \(\pi\) λ2374 or λ2382, we would expect to see absorption elsewhere in the spectrum from species in a similar ionization state. (In the example, Fe \(\pi\) λ2600 would fall in the range 2015–2630 Å and have \(W_\lambda > 0.7\ \text{Å}\); the 1 σ equivalent width limit, discussed in § 3.3, is 0.06 Å in this region of the spectrum.)

The most likely identification for this pair of lines is the C \(\tau\) doublet at 1548 and 1550 Å due to an intervening redshift system at \(z = 0.549\). The separation of the pair of detected absorption lines is 4.5 ± 0.2 Å, while the redshifted separation of the C \(\tau\) doublet should be 4.00 Å, a 2.5 σ difference. Also, the ratio of the two lines, \(W_{\lambda 2402}/W_{\lambda 2397} = 0.67 ± 0.11\), is consistent with the expected ratio of the C \(\tau\) doublet in the optically thin limit. Under this scenario, the lower ionization lines of Si \(\pi\) \(\lambda\) 1526, Al \(\pi\) \(\lambda\) 1670, and Al \(\pi\) \(\lambda\) 1854,1862 would also be shifted into the observed spectral region. These lines are undetected (\(W_\lambda < 0.05\ \text{Å}\) for the Si \(\pi\) line, \(W_\lambda < 0.04\ \text{Å}\) for the Al \(\pi\) and Al \(\pi\) lines), but this is not particularly surprising if the absorbing gas is in a highly ionized state. Unfortunately, we cannot confirm this suggestion by observing other high-ionization lines, since the strong lines of Si \(\tau\) \(\lambda\) 1393,1402 lie below the wavelength limit of our observations.

Another possible pair with the same fractional line separation as the observed features are the O \(\tau\) \(\lambda\) 1302 and the Si \(\pi\) \(\lambda\) 1304 lines, which would have a redshift of 0.841. However, we rule out this identification due to the absence of other strong low-ionization absorption lines (e.g., C \(\pi\) \(\lambda\) 1334, Si \(\pi\) \(\lambda\) 1526, both with limits of \(W_\lambda < 0.04\ \text{Å}\)) at the same redshift.

**QSO 1124+271.**—We have discovered strong Fe \(\pi\) and Mg \(\pi\) absorption at \(z = 0.152\) from a system situated between this quasar and the foreground cluster. These features are noted by tick marks in the appropriate panel of Figure 1. While a complete curve-of-growth analysis of this spectrum is beyond the scope of the current work, we can use the line strengths of these metal transitions to estimate the hydrogen content of this absorber.

Column densities can be determined for optically thin lines by using the relation (see, e.g., Spitzer 1978)

\[
N = 1.13 \times 10^{20} W_\lambda(\text{Å})/f \lambda^2(\text{Å}) \text{ cm}^{-2}.
\]

An examination of the measured Fe \(\pi\) line ratios shows these lines to be approximately optically thin, since the value of \(W_\lambda/\lambda^2\) scales almost linearly with the oscillator strength, \(f\) (taken from Morton 1991). If we use this assumption, we obtain a column density of \(N(\text{Fe }\pi) = 2.6 ± 0.2 \times 10^{13} \text{ cm}^{-2}\) from the three strongest Fe \(\pi\) lines.

To obtain the total Fe column, we need to know the column density of Fe in each stage of ionization. We do not have enough information about this absorber to determine its ionization structure, since this depends strongly on the optical depth of the cloud and the ionizing radiation field. However, we can use the Fe \(\pi\) column determined as a lower limit to the total Fe column, thereby obtaining a lower limit to the total H column. Using the solar Fe abundance of \(\log N_{\text{Fe}} = 7.67\) from Anders & Grevesse (1989), we find that the total H column density in this absorber is \(N_H > 5.6 ± 0.5 \times 10^{17} \text{ cm}^{-2}\), assuming solar metallicity. It is likely that Fe is depleted onto grains, so the “apparent” metallicity might be significantly lower than solar, perhaps by as much as a factor of 10–100. Thus, the H column could be as high as \(N_H \sim 10^{19–20} \text{ cm}^{-2}\), which would place the absorber in the canonical regime of the Lyman limit systems.

Imaging at \(V\) band with the MDM 1.3 m telescope yielded no evidence of faint structure superimposed on or near the
quasar. (See Fig. 2.) The 600 s total integration time reached a 3 $\sigma$ limiting surface brightness of 23.2 $V$ magnitudes arcsec$^{-2}$, which rules out the inner region of a typical galaxy. There are several objects which have profiles indicative of galaxies and lie within 40'' of the quasar sight line, or 160 kpc at $z = 0.152$. The field is centered on $\alpha = 11^h 27^m 36.3^s, \delta = +26^\circ 54' 51''$ (J2000); north is up, and east is to the right.

QSO 1258+285.—This spectrum appears to contain several Ly forest lines bluerward of the quasar Ly$\alpha$ and Ly$\beta$ emission lines. It is difficult to identify absorption from the intervening cluster gas against this forest. In particular, the region where we would expect to find Mg II absorption lies directly on the Ly$\alpha$ emission from the quasar, making it impossible to separate true absorption from structure in the emission line. There appears to be absorption in some of the regions where we expect to find Fe II absorption lines from the cluster. However, one of the strongest Fe lines, Fe II λ2600, is undetected, so we conclude that Fe II absorption at the cluster redshift is unlikely. Absorption at the predicted locations of the other Fe II lines is probably due to Ly forest lines.

Since the quasar Ly$\beta$ line is shifted into our wavelength region, we can attempt to match corresponding Ly$\beta$ and Ly$\alpha$ forest lines. For example, the doublet seen at 2280 Å is repeated at 2700 Å, making this a likely Ly$\beta$/Ly$\alpha$ pair. Other such pairs are observed at 2320/2750 Å and 2415/2860 Å, the latter of these being strong absorption near or within the quasar. The features seen between 2450–2620 Å could be Ly$\alpha$ forest lines; however, their Ly$\beta$ counterparts would lie below our short-wavelength cutoff. For redshift determination of these and other ambiguous features in Table 2, we assume they are Ly$\alpha$ lines.

### 3.3. ICM Metal Absorption Limits

We can place an upper limit on the equivalent width of any expected absorption lines simply by using the noise calculations performed by the line-searching software. The upper limits correspond to a maximum velocity dispersion of $\sigma = 1200$ km s$^{-1}$ and are such that these lines, if present, would fall on the linear portion of the curve of growth. The column density for a weak (optically thin) line can be determined in the usual fashion using the relation given in equation (1). After correcting the equivalent width limits for redshift, we found upper limits to the column density of each species with lines falling in our spectral range. We employed a weighted average over all lines of a given species to further constrain the column density, weighting by the expected line strength and then adding individual line contributions in quadrature. The resulting 1 $\sigma$ upper limits to the column densities for each cluster are listed in Table 3, along with the wavelength and $f$-value of the strongest expected transition of each species.

### 4. DISCUSSION

#### 4.1. Cool Gas Covering Fraction

We have placed strict constraints on the amount of low-ionization absorbing material present in rich clusters of galaxies, beyond a radius of 300 kpc from the center. If we assume a covering fraction approaching 100%, then the column densities of the species in Table 3 are $N \leq 10^{12}$–$10^{13}$ cm$^{-2}$.

### TABLE 3

#### Column Density Upper Limits

| Species | $\lambda$ (Å)$^a$ | $f^b$ | A21 | A151 | A754 | A1267 | Coma | A1795 |
|---------|------------------|-------|-----|------|------|-------|------|-------|
| Al i  ..... | 2264.16 | 0.133 | 13.08 | 13.08 | 13.13 | 12.69 | 13.19 | 13.10 |
| Ca i  ..... | 2151.47 | 0.020 | 13.68 | 13.64 | 13.68 | 13.56 | 14.12 | 13.61 |
| Fe II ..... | 2382.77 | 0.343 | 12.64 | 12.62 | 12.53 | 12.41 | 12.94 | 12.51 |
| Mg II ..... | 2852.96 | 1.730 | 11.83 | 11.75 | 11.76 | 11.53 | 12.83 | 11.63 |
| Mn II ..... | 2796.35 | 0.629 | 12.28 | 12.18 | 12.21 | 11.99 | 12.51 | 12.11 |
| Na I ..... | 2576.88 | 0.351 | 12.43 | 12.40 | 12.38 | 12.19 | 12.40 | 12.30 |
| Si i  ..... | 2853.72 | 0.002 | 14.96 | 14.90 | 14.89 | 14.68 | 14.89 | 14.83 |
|       | 2515.07 | 0.236 | 12.87 | 12.82 | 12.85 | 12.65 | 13.46 | 12.78 |

$^a$ Wavelength of the strongest transition for each species in the observed wavelength range.

$^b$ Oscillator strength, taken from Morton 1991.

$^c$ The 1 $\sigma$ upper limit to the column density for individual clusters.

$^d$ The Fe II and Mg II transitions are the strongest lines expected from low-ionization absorbing gas within the observed spectral range.
cm$^{-2}$, and there is little low-ionization cool gas in this region of the ICM. Our results are consistent with those of Koeke- moer et al. (1998), who found similar limits to $N$ for a variety of species along a single line of sight in Abell 1030. Alternatively, the results permit us to place constraints on the covering fraction of cool absorbing gas. With six independent lines of sight producing nondetections for the strongest expected line (Mg $\text{ii}$ $\lambda 2796$), the covering fraction of low-ionization gas with $N$(Mg $\text{ii}$) $\geq 3 \times 10^{12}$ cm$^{-2}$ must be less than 40%, at the 95% confidence level.

4.2. Efficiency of Ram-Pressure Stripping

The lack of cool ICM material implies either a low rate of production or a relatively short lifetime as low-ionization gas. Of the three gas production mechanisms described above, we expect galactic ram-pressure stripping to be the dominant source of cool ICM gas within the range of projected radii we are considering (0.3–1.4 Mpc). The efficiency of stripping depends on the hot gas density and the velocity of galaxies through the ISM. Based on the numerical modeling of Gaetz, Salpeter, & Shaviv (1987), Soker et al. (1991) identify a stripping condition for a typical elliptical galaxy as it passes through the ICM:

\[
\left( \frac{n_p}{10^{-3} \text{ cm}^{-3}} \right) \left( \frac{v}{10^3 \text{ km s}^{-1}} \right) ^{2.4} \lesssim 0.1 \left( \frac{L_B}{10^{11} \text{ L}_\odot} \right) ^{0.2},
\]

where $n_p$ is the proton number density of the local ICM, $v$ is the velocity of the galaxy, and $L_B$ is the luminosity of the galaxy. If this condition is met, then a galaxy will lose at least half of its gas via stripping. Note that this condition assumes the elliptical galaxy scaling relations of Davies et al. (1983) and a typical mass-loss rate from evolved stars of $\dot{M} \approx 1.5 \times 10^{-11} M_\odot$ yr$^{-1}$ $L_\odot^{-1}$ (Renzini & Buzzoni 1986).

If we assume that the density distribution in the cluster follows a $\beta$ model of the form

\[
n(r) = n_0 \left( 1 + \left( r/r_c \right) ^2 \right) ^{-3/2},
\]

where $n_0$ is the central gas density and $r_c$ is the core radius, then we may define a stripping radius $r_s$ such that

\[
r_s/r_c \approx 0.023 \left( \frac{n_0}{10^{-3} \text{ cm}^{-3}} \right) ^{-1} \times \left( \frac{\sigma}{10^3 \text{ km s}^{-1}} \right) ^{-2/3} \left( \frac{\beta}{2} \right) ^{-1/2}.
\]

For radii smaller than $r_s$, the density of the ICM is sufficient to effectively strip gas from an elliptical galaxy moving through it. Here we assume all galaxies have the rms velocity $v = \sqrt{3} \sigma$, where $\sigma$ is the one-dimensional galaxy velocity dispersion. We have also made the conservative assumption that the galaxies being stripped are large $L_*$ ellipticals; smaller galaxies have shallower potential wells and are able to have gas removed by a more rarefied ICM. Thus, the stripping radius will be even larger for smaller galaxies.

To determine the stripping radii for the clusters in our sample, we used recently released $\beta$ model fitting based on Einstein data (Jones & Forman 1999). Four of our six clusters are included in this X-ray sample; of these four, three have data of sufficient quality to allow a full-parameter fit to the $\beta$ model (Coma, Abell 754, and Abell 1795). The fourth (Abell 21) has data which allows only a one-parameter fit to $r_s$ while keeping $\beta$ fixed at a typical value of 0.6. The $\beta$ model parameters thus derived by Jones & Forman (1999) are shown in Table 4, along with velocity dispersions from Struble & Rood (1999), our calculated values of the stripping radius $r_s$, and the projected radius $r_{proj}$ of the quasar line of sight. All four sight lines lie well within our calculated stripping radii, therefore we expect stripping to be a fairly effective gas production mechanism for these clusters.

It is difficult to draw conclusions about the efficiency of stripping in the remaining two clusters based on currently existing data. We have no information about the density distribution of these clusters. Abell 151 has a velocity dispersion of 669 km s$^{-1}$ (Struble & Rood 1999), similar to that of Abell 21, but the line of sight is projected 0.92 Mpc out from the cluster center. Even assuming a density distribution similar to the other clusters, this might be near the region where stripping becomes less important. Abell 1267 has a very low velocity dispersion (190 km s$^{-1}$; Struble & Rood 1999); it is possible that the galaxies in this cluster are simply not moving quickly enough to be stripped of their gas by the ICM. In the following discussion, we assume that the sight lines through all six clusters sample a volume within the stripping radius; however, we note here that this may not be the case for two of the clusters.

4.3. Lifetime of the Low-Ionization Gas

If we assume our model of galactic stripping is correct, we can estimate the expected cool gas covering fraction produced in this way. A typical cluster member galaxy loses $1 M_\odot$ yr$^{-1}$ from its evolved stars, creating a stream of solar-metallicity gas as the galaxy moves through the ICM (Soker et al. 1991). For a galaxy moving at 500 km s$^{-1}$, the length of this wake will be $500(t/10^9 \text{ yr})$ kpc, where $t$ is the lifetime of the low-ionization gas (discussed below). With a typical width of 20 kpc, the gas stream will have an H$\text{i}$ column density of $N(\text{H} \text{ i}) \approx 2 \times 10^{19}$ cm$^{-2}$ and will be readily observable in Ly$\alpha$ and metal-line absorption. A rich cluster with 100 such galaxies undergoing stripping within an inner radius of 1.5 Mpc would have a cool gas covering fraction of $\sim$$15\% (t/10^9 \text{ yr})$, without making allowances for overlap or projection effects which would further reduce the fraction.

We can place limits on the lifetime of the cool gas in a simple way by using our determination of the covering fraction of $\leq 40\%$. If we again neglect projection effects, which at this covering fraction could indeed be important, the result from the exercise above implies that the lifetime of the low-ionization gas is $t \lesssim 2.5 \times 10^9$ yr. The ultimate fate of this cool gas is still a matter of uncertainty; some possible scenarios are discussed in the following section.
5. CONCLUSIONS

We have searched for UV resonance absorption against quasars projected behind six clusters of galaxies and have obtained the following results:

1. No absorption features are detected at the cluster redshift along any of the sight lines, leading to upper limits on the individual cluster column densities of $N$(Mg ii, Fe ii) < $10^{12}$–$10^{13}$ cm$^{-2}$.

2. Several systems distinct from the Milky Way and clusters under study are detected. These include an H i outflow or cloud close the redshift of QSO 0107–156; a possible $z = 0.549$ C iv absorption system along this same line of sight; and a $z = 0.152$ Mg ii absorption system, which is likely to be a Lyman limit system, toward QSO 1124+271.

3. The lack of cluster absorption along these six sight lines implies that the covering fraction of cool gas at intermediate cluster radius is <40% to the 95% confidence level.

4. Ram-pressure stripping of cool gas from member galaxies is likely to occur at these radii in four of the six clusters, with the remaining two lacking sufficient data for this analysis. Assuming stripping to be effective along all six sight lines, and given a cluster with typical properties, we estimate the lifetime for low-ionization gas to be less than about 2.5 x 10$^9$ yr.

This cool gas can have two possible fates. First, it can thermally evaporate and join the hot ICM in a process driven by thermal conduction. The efficiency of this process depends on the strength and homogeneity of the intracluster magnetic field (Cowie & McKee 1977; Mathews 1990), which are poorly understood. Second, the gas can remain cool and nonbuoyant in the ambient ICM and thus fall to the center of the cluster in a free-fall time ($t_f$ < 10$^9$ yr). It is expected that mixing and thermal evaporation is the dominant fate of gas stripped from galaxies outside of the cooling radius, which is where our six quasar lines of sight lie. Alternatively, the gas may be consumed through star formation as it free-falls, but on a timescale shorter than the free-fall time in the cluster. Under this scenario, we would expect the presence of $< 10^{12} (M/10^9 M_\odot \text{ yr}^{-1}) M_\odot$ of stars distributed throughout the cluster. Assuming a fairly normal initial mass function, such a population would produce $< 3 \times 10^{11}$ L$_\odot$ of visible light, or the equivalent of a few normal galaxies. Recent studies have shown that the diffuse light in typical rich clusters is several orders of magnitudes brighter than this, perhaps equaling the luminosity from galaxies in the inner parts of the cluster (see, e.g., Bernstein et al. 1995; Mendez et al. 1997). Thus, it would be difficult to observe the presence of a stellar component created through galactic stripping.

The above treatment assumes that galactic stripping is effective as described by the Gaetz et al. (1987) and Soker et al. (1991) scenarios. It is possible that the observed lack of cool gas may result from the ICM not being dense enough to strip galaxies of their gas. Further observations of cluster galaxies are needed to test these models. In addition, although low-ionization gas does not appear to have a large covering fraction in galaxy clusters, little is known about higher ionization state gas, as is often identified through C iv and Si iv absorption. There are expectations that searches for higher ionization absorption will be more successful, based upon a few observations through other clusters. In an observation toward 3C 273, which lies behind the outer part of the Virgo cluster, Lyα absorption was detected in the redshift of the cluster (Bahcall et al. 1991). It has an H i column density of at least $4 \times 10^{14}$ cm$^{-2}$ and has detectable high-ionization metal absorption lines (Hurwitz et al. 1998 and references therein). In the future, we hope to study whether clusters are sites of high-ionization absorption lines and whether they produce Lyα absorption, thus completing the study of the absorbing properties of galaxy clusters.

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