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THE MULTIPHASE INTRACLUSTER MEDIUM IN GALAXY GROUPS PROBED BY THE Lyα FOREST

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ABSTRACT

The case is made that the intracluster medium (ICM) in present-day spiral-rich galaxy groups probably has undergone a much slower evolution than that in elliptical-rich groups and clusters. The environments of protoclusters and protogroups at $z > 2$ are likely similar to spiral-rich group environments at lower redshift. Therefore, like the ICM in spiral-rich groups today, the ICM in protogroups and protoclusters at $z > 2$ is predicted to be significantly multiphased. The QSO Lyα forest in the vicinity of galaxies is an effective probe of the ICM at a wide range of redshift. Two recent observations of Lyα absorption around galaxies by Adelberger et al. and by Pascarelle et al. are reconciled, and it is shown that observations support the multiphase ICM scenario. Galaxy redshifts must be very accurate for such studies to succeed. This scenario can also explain the lower metallicity and lower hot gas fraction in groups.

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

1. INTRODUCTION

Hot X-ray gas (with temperatures of $\sim 10^6$–10^8 keV) is found in all galaxy clusters and groups in which it can currently be detected (see Burstein & Blumenthal 2002; Mulchaey 2000, hereafter M00). The fact that velocity dispersions of groups and clusters correlate well with X-ray temperature has shown that galaxy groups are distinct physical entities, not transient systems (M00; Mulchaey et al. 2003). In this Letter, this hot gas is referred to as the intracluster medium (ICM), with the understanding that this term also includes galaxy groups in its definition.

Cooling times for hot gas is a trivariate function of its temperature, metallicity, and density (Sutherland & Dopita 1993). As such, in present-day galaxy groups and clusters, hot gas turns into cooler, more neutral gas in at least two ways. In the centers of clusters, the high density and high metallicity of the hot gas combine to predict relatively short cooling times (hundreds of millions of years; see Fabian et al. 2002), while in the less dense outer parts of clusters, the cooling times are much longer. Separately, in groups with low-velocity dispersion (i.e., those dominated by spiral and irregular galaxies; see Mulchaey et al. 1996; Mulchaey & Zabludoff 1998; Zabludoff & Mulchaey 1998), the still relatively metal rich hot gas can quickly become neutral because of its lower temperature and its interaction with neutral hydrogen in the galaxies in these groups (Burstein & Blumenthal 2002). Thus, the ICM of spiral-rich galaxy groups today (e.g., the Local Group) can be considered to be multiphase.

The question then is how multiphase is the ICM at high redshift? Answering this question is crucial to understanding the evolution of gas in galaxy groups and clusters. In this Letter, the case is made that a multiphase ICM exists in high-z galaxy groups and clusters as they are forming (§ 2). The evidence for this conjecture that comes from the Lyα forest is provided in § 3, where it is shown how to reconcile two recent observations that somewhat contradict each other. Further implications of the multiphase ICM are discussed in § 4. An $\Omega = 0.3$, $\Lambda = 0.7$ universe is assumed in this Letter, and the distance scales quoted below are all comoving.

2. A LIKELY MULTIPHASE ICM AT HIGH REDSHIFT

From present-day hot ICM gas, two things must be true when groups and clusters are forming. First, because all hot ICM gas has a significant abundance of metals (0.1–0.5 times solar; M00), much of this hot gas had to have seen the interiors of stars. Second, because of the strong correlation of group/cluster velocity dispersion with X-ray temperature (M00), the gas became hot through heating by supernovae and stirring by the virial motion of the galaxies. This observational picture is consistent with the current hierarchical, clustering, merging scenario, which predicts that today's galaxies formed from smaller objects in an environment dominated by cold dark matter (e.g., Navarro, Frenk, & White 1995).

From studies of galaxy groups and clusters in the nearby universe (see the Nearby Galaxies Catalog by Tully 1988), the vast majority of nearby galaxies are well associated with either a galaxy group or a galaxy cluster. Of the nearly 2450 galaxies within 3000 km s^{-1} distance of our Local Group that are in the Nearby Galaxies Catalog, only 35 are not put in a group, cloud, or cluster. And most of these 35 galaxies are within less than 1 Mpc of a group or cluster. Furthermore, the majority of galaxies in the Nearby Galaxies Catalog are in galaxy groups (most of which are low-velocity dispersion, spiral-rich groups), not in elliptical galaxy–dominated clusters such as the Virgo Cluster. As such, it is reasonable to assume that if galaxies are seen at high redshift, they are more likely to be part of a group (even though groups are hard to identify at high z).

When galaxies are in the beginning throes of formation, the ICM should have similar properties to the diffuse $\sim 10^4$ K intergalactic medium (IGM), whose temperature scales with the density as $T \propto \rho^{\alpha}$, with $\alpha = 0.3$–0.6 (Hui & Gnedin 1997). At the start of galaxy formation (as well as group and cluster formation), the density of the ICM may not be much greater than the cosmic mean; hence, the ICM cannot be initially much hotter than 10^4 K. At this stage, the ICM is relatively uniform in the gravitational well.

The ICM will become hotter as galaxies evolve and inject hot gas and energy into it. However, the heating before $z = 2$ is not strong enough to heat the ICM to 10^6–10^8 K globally.

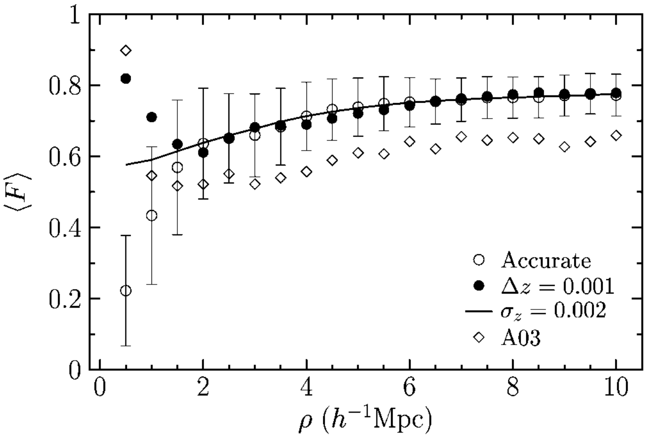

Fig. 1.—Mean Lyα flux around galaxies. The open circles, filled circles, and the solid line are the cases with no error in redshift, a systematic error of $\Delta z = 0.001$, and a Gaussian error with dispersion $\sigma_z = 0.002$, respectively. The error bars of the three are similar but are only plotted for the open circles for clarity. The diamonds are from A03. The segment of the Lyα forest in our analysis is from $z = 2.16$ to 2.70, so the cosmic mean flux is higher than that at $z = 3$. This leads to the difference between A03 and the rest of the data at large impact parameters.

Supernova heating is proportional to the star formation rate, which peaks at $z \simeq 1$–2 (Steidel et al. 1999). Virial shocks are not likely to happen at $z > 2$ or in systems less massive than $10^{11}\ M_\odot$ (Birnboim & Dekel 2003). Other sources of heating are active galactic nuclei (AGNs), whose number densities increase sharply toward $z \simeq 2$ but do not evolve much beyond $z \simeq 2$ (Miyaji, Hasinger, & Schmidt 2000). Yet recent observations around protoclusters (Adelberger et al. 2003, hereafter A03) imply that AGN heating has not drastically affected the ICM at $z \simeq 3$. Therefore, AGNs may not have a primary role in heating the ICM in all clusters and groups.

On the other hand, cooling of gas at its higher density at higher redshift is relatively quick. This is supported by the argument that the metallicity of this gas had to have been seeded quickly by the first generations of star formation. As a result, the metallicity of the high-z ICM hot gas probably is not too much lower than it is today. It is therefore reasonable to assume that pockets of moderately metal rich, 10^4–10^5 K gas exist in $z > 2$ protogroups and protoclusters.

The relatively weak heating and quick cooling necessarily lead to a widely distributed, multiphase ICM both in protoclusters and in protogroups at high redshift. Spiral-rich groups can maintain such a distributed, multiphase ICM since they receive less energy input from fewer galaxies and since many of their galaxies have neutral gas with which the cooler hot gas can interact (Burstein & Blumenthal 2002). In other words, the ICM in present-day spiral-rich groups probably has undergone a much slower evolution than the ICM in rich clusters and elliptical-rich galaxy groups. With this scenario, the environments of protoclusters and protogroups at $z > 2$ are expected to be similar to those in present-day spiral-rich galaxy groups, and therefore the ICM in all galaxy systems is multiphase at $z > 2$.

In contrast, present-day rich clusters and elliptical-rich groups cannot preserve such a distributed multiphase ICM since their member galaxies supply large amounts of virial energy to the ICM. This picture is consistent with the fact that rich clusters are mostly observed at $z < 1$ (Henry et al. 1992), and the X-ray–emitting ICM in clusters and groups has to be mostly formed between $z = 2$ and today.

3. THE MULTIPHASE ICM PROBED BY THE Lyα FOREST

The above scenario predicts that foreground galaxies, through a strongly multiphased ICM that contains a large number of strong Lyα absorbers, can influence the Lyα forest of a background QSO. Accordingly, one expects to see a higher number of strong Lyα absorption lines and a lower mean Lyα flux at smaller impact parameters between foreground galaxies and background QSOs. This gives us a practical criterion: an ICM is strongly multiphased if it contains stronger fluctuations (measured by Lyα absorptions) than the IGM.

3.1. *Observations*

This scenario is consistent with a number of observations. Lanzetta et al. (1995), Chen et al. (1998), and Pascarelle et al. (2001, hereafter P01) find that galaxies that are not influenced by the QSOs (i.e., the “far sample” of galaxies in P01) that are at impact parameters $\rho \leq 180\ h^{-1}$ kpc are much more often associated with Lyα absorption in the background QSO spectrum than those at $\rho > 180\ h^{-1}$ kpc. The rest-frame equivalent widths W of absorption tend to increase as ρ decreases from 1 h^{-1} Mpc to 10 h^{-1} kpc (P01, Fig. 1).

It is conservative to assume that most galaxies in the far sample are in groups (the same as they are in the local universe). The line statistics thus suggest that the ICM in groups does contain more strong Lyα absorbers than the diffuse IGM. The far sample in P01 ranges from $z = 0.02$ to 1, over which groups are seen to contain sub-keV gas (M00; Xue & Wu 2000), consistent with a multiphase ICM. On the other hand, Lyα lines around galaxies that are subject to QSO influence are almost always weaker than those in the far sample, and they do not depend much on the impact parameter (P01). This shows that the ICM cannot remain multiphase under the influence of QSOs, and consequently AGNs may be responsible for heating the ICM in some groups and clusters at $z \lesssim 1$.

At a higher redshift, $z \simeq 3$, A03 show that mean Lyα transmissivity generally increases with increasing impact parameter between foreground Lyman break galaxies (LBGs) and background QSOs. It reaches a cosmic mean transmissivity of 0.67 at $\rho \gtrsim 6\ h^{-1}$ Mpc. This result indicates that the ICM at $z \simeq 3$ has a higher overall neutral fraction than the IGM. Since H I concentrates where the Lyα lines are, the Lyα lines near the LBGs must have substantially larger equivalent widths than the Lyα forest lines. This is consistent with both the line statistics above and a multiphase ICM.

LBGs are more likely to be massive systems (Baugh et al. 1998) that reside in dense regions, where groups and clusters are found today. This strengthens the argument that Lyα absorption associated with the LBGs out to 6 h^{-1} Mpc is due mostly to the ICM. In fact, the LBGs in A03 are claimed to likely be in protoclusters, of which at least a few will evolve into rich clusters at $z = 0$ that contain most of their baryonic mass in X-ray–emitting hot gas.

3.2. *The Discrepancy*

Despite the general agreement, flux statistics in A03 are not consistent with line statistics at $\rho < 0.5\ h^{-1}$ Mpc. An increase of mean flux from 0.55 at 1 h^{-1} Mpc to 0.9 at 0.5 h^{-1} Mpc (see Fig. 1) is reported in A03.

LBGs are strong UV sources, and the escape fraction of ionizing photons from LBGs at $z = 3$ is higher than that from local starburst galaxies (Deharveng et al. 2001; Steidel, Pettini, & Adelberger 2001; Giallongo et al. 2002). It is possible that the rise of the mean flux close to LBGs at $z = 3$ is due to the photoionization by the LBGs themselves (similar to the proximity effect of QSOs; e.g., Bajtlik, Duncan, & Ostriker 1988; Giallongo et al. 1996; Scott et al. 2000), which is absent in low-redshift galaxies. One can roughly estimate the size of the influence of LBGs as follows. If the luminosity of a typical QSO is 10^{46} ergs s^{-1} and if it has a line-of-sight (LOS) proximity zone of 36 h^{-1} Mpc (4000 km s^{-1} at $z = 3$), then an LBG with a luminosity of 10^{41} ergs s^{-1} would create a highly ionized (higher than the IGM) bubble with a radius of at most 0.8 h^{-1} Mpc,\ where a proportionality between volume and luminosity has been assumed. The radiation of QSOs is most likely anisotropic, as suggested by the null detections of the foreground QSO proximity effect (Crotts 1989; Møller & Kærgaard 1992; Liske & Williger 2001), so that the relatively isotropic radiation from LBGs should considerably reduce their radius of influence. In addition, QSOs have harder spectra than LBGs, which help to create larger proximity zones, owing to larger fractions of high-energy photons that can travel farther to ionize H I because of their smaller cross sections for photoionization. Therefore, an estimate of 0.8 h^{-1} Mpc is a conservative upper bound for the radius that can be affected by radiation from LBGs. Alternatively, A03 suggest that supernova-driven winds with a sustaining speed of 600 km s^{-1} for a few hundred million years may be able to deplete H I and reduce Lyα absorption in a region of comparable size.

Regardless how the highly ionized bubble is created, however, Weinberg et al. (2003) show with hydrodynamical simulations that even if one removes all H I within 1.5 h^{-1} Mpc from LBGs in real space, the mean flux at $\rho < 0.5$ h^{-1} Mpc is still lower than 0.67. It is because the infalling H I from large radii could be easily seen within 0.5 h^{-1} Mpc in redshift space. This is similar to the finger-of-God effect, which smears real-space information along the LOS. For example, the Hubble constant at $z = 3$ is 446 h km s^{-1} Mpc^{-1}, so that an infall speed of 120 km s^{-1} will enable Lyα absorbers at a LOS distance of 1.5 h^{-1} Mpc from an LBG in real space to appear less than 0.5 h^{-1} Mpc from the LBG in redshift space. Since the peculiar velocity of a gas clump in a cluster easily exceeds 120 km s^{-1}, it will completely erase the LBG bubble in redshift space.

In summary, the flux statistics found by A03 are incompatible with the line statistics found by P01 at $\rho < 0.5$ h^{-1} Mpc. This difference cannot be easily attributed to ionization by LBGs themselves, through either radiation or winds, unless LBGs could ionize an unrealistically large volume (radius $\gg 1$ h^{-1} Mpc) that cannot be erased by the virial motions of gas clouds.

3.3. *Resolving the Discrepancy: Redshift Errors*

The mean flux at an impact parameter from a galaxy is meaningful only if it is calculated within a compatible distance from the galaxy along the LOS. The rms error of the galaxy redshift is $\sigma_z = 0.002$ in A03, which corresponds to 1.3 h^{-1} Mpc at $z \simeq 3$. In turn, redshift errors can lead to an inaccurate estimate of the mean flux within $\rho = 1.3$ h^{-1} Mpc. A03 evaluate the mean flux in their data using the flux-galaxy correlation function to suppress the effect of redshift error. This method only helps if the sample is large. However, A03 have only three galaxies at $\rho < 0.5$ h^{-1} Mpc without Lyβ contamination (three more with Lyβ contamination), so redshift errors could still alter the mean flux within $\rho = 1.3$ h^{-1} Mpc.

The effect of a small redshift error Δz on the mean flux is examined using the Keck high-resolution spectrum of QSO HS 1700+64 (for observational details and data reduction techniques, see Kirkman & Tytler 1997). This QSO is at $z = 2.74$, and the spectral resolution of the data used is 8 km s^{-1}. Only the segment between $z = 2.16$ and 2.70 is analyzed in order to exclude Lyβ absorptions and the QSO proximity zone. In an idealized case in which a galaxy is at the center of a Lyα line, the mean flux of the Lyα forest around the galaxy redshift should increase with the scale over which this mean flux is calculated, until it reaches the cosmic mean.

A mock sample of 59 galaxies is made by assigning the positions of strong Lyα lines (4 Å $\geq W \geq 0.5$ Å) to galaxies. If two lines are closer than 2.5 Å, the stronger one remains. The line width criterion is arbitrary, but it only contributes to the dispersions and details, not the general trend. Line widths are adopted from Dobrzycki & Bechtold (1996) with corrections to line positions. Impact parameters are not assigned; rather mean fluxes are calculated within the LOS distances (still reported as ρ) that are equal to the impact parameters as argued above.

The mean flux around accurate galaxy positions is shown in Figure 1 with open circles, which decreases monotonically as ρ decreases. A small systematic error of $\Delta z = 0.001$ (*filled circles*) can easily raise the mean flux at $\rho \leq 1.5$ h^{-1} Mpc. If the error is Gaussian with a dispersion $\sigma_z = 0.002$ (*solid line*), the mean flux drops slightly from $\rho = 2$ h^{-1} Mpc to $\rho = 0.5$ h^{-1} Mpc, but it never rises at smaller ρ.

The same Gaussian error was tested by A03, but no significant effect was found. If the positions of the few galaxies in A03 at $\rho < 0.5$ h^{-1} Mpc are all off by $\Delta z = 0.002$, one cannot recover a meaningful ensemble average of the mean flux by adding the Gaussian error $\sigma_z = 0.002$ to their positions. The positional error of a small number of galaxies is simply not well characterized by a Gaussian distribution. More observations are needed to conclusively establish the mean flux at small impact parameters.

If the deficit of Lyα absorption at $\rho < 0.5$ h^{-1} Mpc is the result of errors in galaxy positions, then the flux statistics and the line-counting statistics give a consistent picture of a multiphase ICM that exists in high-z galaxy aggregations and low-z groups. If not, one will have to explain how LBGs ionize a sphere of radius $\gg 1$ h^{-1} Mpc in real space.

3.4. *Neutral Hydrogen in the ICM at $z \simeq 3$*

Given the mean flux $\langle F \rangle$, one can estimate the density of neutral hydrogen $n_{\rm H}$ using (Peebles 1993)

$$n_{\rm H} \simeq 2.4 \times 10^{-11} \Omega^{1/2}\ h(1+z)^{3/2} \ln \langle F \rangle^{-1}. \qquad (1)$$

The H I column density $N_{\rm H}$ at $z = 3$ is roughly

$$N_{\rm H} \simeq n_{\rm H} l \simeq 8.1 \times 10^{13} \ln \langle F \rangle^{-1} (l/h^{-1}\ {\rm Mpc})\ {\rm cm}^{-2}, \qquad (2)$$

where l is the (comoving) LOS path length through the ICM. With the lowest mean flux, $\langle F \rangle = 0.52$, near LBGs in A03, and $l = 12$ h^{-1} Mpc for a spherical ICM that extends to 6 h^{-1} Mpc (§ 3.1), equation (1) yields an upper limit of $N_{\rm H} =$

6.4×10^{14} cm^{-2} in the ICM at $z = 3$. This is several orders of magnitude lower than Galactic values, so it can easily escape detection from 21 cm radio and other observations, even if it still exists in the ICM today.

4. DISCUSSION AND CONCLUSIONS

The Lyα forest in the vicinity of foreground galaxies is potentially a great probe for studying the ICM. Caution must be taken, however, since knowing the accuracy of the galaxy redshift is crucial when probing at small impact parameters. Nevertheless, the available observations point to a multiphase ICM at $z = 3$, which exists partially in the form of strong Lyα absorbers. It is also evident from the Lyα forest that a multiphase ICM is preserved in present-day spiral-rich galaxy groups, consistent with what can be predicted about the cooling times for the hot gas in such galaxy groups (Burstein & Blumenthal 2002). An independent piece of evidence comes from the recent discovery of the warm-hot 10^5–10^7 K *intragroup* medium through observations of the high-velocity O VI absorption clouds around our Galaxy at a likely distance of $\gtrsim$100 kpc (e.g., Nicastro et al. 2003). For rich clusters, the ICM may have been homogenized by galaxies, so that it is unlikely to be multiphase, except in core regions where cooling times are short, and therefore expected to show much less Lyα absorption than the IGM.

It is found that ionization by LBGs themselves via radiation or supernova-driven winds cannot easily account for the lack of Lyα absorption at $\rho < 0.5\ h^{-1}$ Mpc in A03 because LBGs do not have sufficient energy to ionize a region of a size $\gg 1\ h^{-1}$ Mpc in real space. Errors in galaxy positions can cause the apparent rise of the mean flux at $\rho < 0.5\ h^{-1}$ Mpc found by A03.

The origin of the multiphase ICM is the competition between heating and cooling in these environments. The detailed properties of the absorbers are not well determined by Lyα observations alone. This is because even though cool (~10^4 K) and dense absorbers are common at $z = 3$, shocked gas clumps appear more often at low redshift. These gas clumps can have high H I column densities (e.g., Davé et al. 1999), in spite of higher temperatures ($\gtrsim 10^5$ K).

The existence of a multiphase ICM requires effective cooling and low heating. This is consistent with groups having a lower fraction of mass in hot gas than do clusters, if a higher fraction of the ICM in groups is kept in cool and warm phases. In addition, since galaxies heat the ICM by feedback and motion, less heating means lower metallicity in the ICM in galaxy groups, which is observed (M00).

A multiphase ICM may also contribute to the excess of entropy in the cores of poor clusters and groups (Ponman, Cannon, & Navarro 1999), which requires a lower electron density than predicted by the hierarchical clustering model. Efficient cooling in poor clusters and groups may reduce the hot gas density in a short time. If this picture is correct, one might circumvent the problem of missing soft X-ray emission encountered by the cooling flow model (Fabian et al. 2001; Wu, Fabian, & Nulsen 2001), which lowers the hot gas density by ongoing cooling.

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