NOT DEAD YET: COOL CIRCUMGALACTIC GAS IN THE HALOS OF EARLY-TYPE GALAXIES

CHRISTOPHER THOM1, JASON TUMLINSON1, JESSICA K. WERK2, J. XAVIER PROCHASKA2, BENJAMIN D. OPPENHEIMER3, MOLLY S. PEEPLES4,9, TODD M. TRIPP5, NEAL S. KATZ5, JOHN M. O’MEARA6, AMANDA BRADY FORD7, ROMEELE DAVE7, KENNETH R. SEMBACH1, AND DAVID H. WEINBERG8

1 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
2 UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA
3 Leiden Observatory, Leiden University, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands
4 Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, CA 90095, USA
5 Department of Astronomy, University of Massachusetts, Amherst, MA 01003-9305, USA
6 Department of Chemistry and Physics, Saint Michael’s College, Colchester, VT 05439, USA
7 Steward Observatory, University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721, USA
8 Department of Astronomy, The Ohio State University, 140 W. 18th Avenue, Columbus, OH 43210, USA

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ABSTRACT

We report new observations of circumgalactic gas in the halos of early-type galaxies (ETGs) obtained by the COS-Halos Survey with the Cosmic Origins Spectrograph on board the Hubble Space Telescope. We find that detections of H1 surrounding ETGs are typically as common and strong as around star-forming galaxies, implying that the total mass of circumgalactic material is comparable in the two populations. For ETGs, the covering fraction for H1 absorption above 1016 cm−2 is ∼40%–50% within ∼150 kpc. Line widths and kinematics of the detected material show it to be cold (T < 105 K) in comparison to the virial temperature of the host halos. The implied masses of cool, photoionized circumgalactic medium baryons may be up to 109–1011 M⊙. Contrary to some theoretical expectations, strong halo H1 absorbers do not disappear as part of the quenching of star formation. Even passive galaxies retain significant reservoirs of halo baryons that could replenish the interstellar gas reservoir and eventually form stars. This halo gas may feed the diffuse and molecular gas that is frequently observed inside ETGs.

Key words: galaxies: formation – galaxies: halos – intergalactic medium – quasars: absorption lines

Online-only material: color figure

1. GAS AND QUenchING IN EARLY-TYPE GALAXIES

The dichotomy of color, star formation rate (SFR), morphology, etc. between spirals and early-type galaxies (ETGs) was established nearly a century ago, and has been highly refined over the past decade (e.g., Baldry et al. 2004; Bell et al. 2004; Faber et al. 2007). Despite long-standing empirical measurements, the physical processes that divide the two populations are still uncertain. The main challenge is to identify the mechanism(s) that quench star formation (SF) and that inhibited it over the past ∼10 Gyr. Dramatically different scenarios have been proposed for how SF is quenched. Ejective feedback is generally caused by the galaxy itself and includes super winds that expel gas (e.g., Springel et al. 2005) or more general heating and stripping of the gas (Tonnesen & Bryan 2009), as well as mergers. Conversely, preventative feedback, such as shock-heating of the gas prior to its accretion (e.g., Dekel & Birnboim 2006) or the disruption of infalling clouds and their diffusion into the galaxy’s gaseous halo (Putman et al. 2011; Bland-Hawthorn et al. 2007) are consequences of ETGs living in massive halos.

The paradigm of “red and dead” galaxies as quiescent, passively evolving stellar systems is being reconsidered in light of findings that a non-negligible fraction of them contain gas and dust, and a subset has experienced recent SF (e.g., Lees et al. 1991; González 1993; Trager et al. 2000; Thomas et al. 2010; Kaviraj 2010). There is also a high incidence of field ETGs with molecular gas (22%; Young et al. 2011), H1 gas (40%; Serra et al. 2012), and ionized gas (73%; Davis et al. 2011). The gas masses are often comparable to those of spirals in both atomic and molecular phases, with MHI ≈ 1–50 × 107 M⊙ (Oosterloo et al. 2010) and MHI = 107–9 M⊙ (Figure 6 of Young et al. 2011). The corresponding SFRs reach up to a few M⊙ yr−1 (Crocker et al. 2011). Nevertheless, most ETGs are quenched, and remain so. These observations raise a new series of challenges. What is the source of the interstellar gas? On what timescale(s) did it arrive? Given this reservoir of cool gas, why does the SFR remain low?

2. THE COS-HALOS SURVEY: MOTIVATIONS AND DATA

Gas entering ETGs from their large-scale surroundings must pass through their circumgalactic medium (CGM), where it is detectable with sensitive UV absorption line tracers (limiting column density NHI ≳ 1013 cm−2). Quasar absorption line studies have attempted to link H1 absorption (generally Lyα only) and nearby galaxies, but the results have been inconclusive, suffering from small sample sizes and the inability to control for galaxy type and SFR. Chen et al. (2001) showed that Lyα absorption is common around galaxies of a wide range of morphological types, whereas Chen & Mulchaey (2009) showed that strong H1 absorbers (NHI > 1014 cm−2) reside primarily in the halos of SF galaxies (see their Figure 13). Wakker & Savage (2009) found ubiquitous H1 around ≥0.1 L* galaxies at 350 kpc scales, but could not separate galaxies by type. Most recently, Prochaska et al. (2011) found that strong Lyα absorption (W ≥ 300 mÅ) arises in galaxy halos—including less

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9 Center for Galaxy Evolution Fellow.
massive ETGs—within ρ ≳ 300 kpc, but the majority of their pairs lie at large radii (only three pairs at ρ < 200 kpc). Careful selection of QSO sightlines is therefore crucial to study the dependence of CGM gas within 150 kpc, and spectroscopy of the host galaxies is important to measure the current SFR and galaxy metallicities.

We designed the COS-Halos survey to probe the inner CGM of L∗ galaxies at z ∼ 0.2 and to test the prevailing theoretical picture of “hot” and “cold” accretion, which might be related to the observed SF dichotomy in galaxies (Kereš et al. 2005; Dekel & Birnboim 2006). COS-Halos has several distinct advantages over previous work for assessing the amount and properties of CGM surrounding ETGs: (1) it systematically covers impact parameters 0–150 kpc and stellar masses log M∗ = 10–11 with galaxies from both color–magnitude sequences selected prior to knowledge of absorption; (2) the wavelength range of COS and the galaxy redshifts (z ≳ 0.1) generally allow for measurements of the weaker H1 Lyman series lines that give better column densities and line-broadening parameters than Lyα alone; and (3) the galaxies are well characterized by ground-based optical measurements of their stellar masses, SFRs, and metallicities. COS-Halos has previously found that highly ionized O v1 in the halos of ETGs occurs at much lower incidence than in star-forming galaxies, such that the presence of O v1 out to ∼ 150 kpc is related to SF (Tumlinson et al. 2011a). We will present the full analysis of the H1 absorption for our complete sample of 50 galaxies in a future paper (J. Tumlinson et al. 2012, in preparation). In this Letter, we present results for 16 ETGs from COS-Halos, showing that their associated H1 gas is plentiful (Section 3), bound (Section 4), cold (Section 5), and may represent a large mass of baryons in their CGM (Section 6).

The COS-Halos survey obtained 39 spectra of QSOs at z < 1 with the Cosmic Origins Spectrograph (COS; Green et al. 2012) on board the Hubble Space Telescope under program GO-11598 (PI: Tumlinson). These data were reduced, co-added, and continuum-normalized with procedures outlined by Meiring et al. (2011), Tumlinson et al. (2011b), and Thom et al. (2011). We measured column densities for the absorption associated with targeted galaxies using both the apparent optical depth technique (Sembach & Savage 1992) and iterative Voigt profile fitting with the measured COS line-spread function (Ghavamian et al. 2009). Our measurements for H1 column density are weighted averages of unsaturated Lyman lines or profile fits to damped absorption. Where all available Lyman series lines are saturated, we set a lower limit to NHI, with the highest-order detected Lyman line. The multi-component Voigt profile fitting yields N, b, and v for components within each system that are used in Section 5.

The medium-resolution Keck and Magellan spectroscopy used to derive the properties of the galaxies in the sample (SFRs, metallicities, etc.) is described fully by Werk et al. (2012). The resulting sample contains 16 galaxies classified as passive and/or early type, based on their lack of SF (sSFR = SFR/M∗ < 10−11 M⊙ yr−1; Werk et al. 2012). We caution that these fields have not been uniformly surveyed for all galaxies down to low-luminosity limits to eliminate all other possible associations, but these observations empirically describe the distribution of gas around ETGs as a function of impact parameter, whatever its source. Figure 1 shows an example of an ETG and star-forming galaxy from our sample. The composite image from the Sloan Digital Sky Survey (SDSS) is shown, along with the Lyα absorption owing to the galaxy.
Both galaxies have similar H\textsc{i} column densities and absorption profiles.

3. STRONG H\textsc{i} IS COMMON AROUND EARLY-TYPE GALAXIES

Figure 2 plots the Ly\textsc{a} rest-frame equivalent width $W_r$ as a function of impact parameter $\rho$ and shows the remarkable similarity in H\textsc{i} strength between the ETG (red) and SF (blue) samples. A Kolmogorov–Smirnov (K-S) test on $W_r$ does not provide significant evidence against the null hypothesis that the two distributions are drawn from the same parent population ($D = 0.32$, $P = 0.19$). The four Ly\textsc{a} non-detections drive the difference in the K-S statistic, and offer a hint that the distributions may be slightly different, but we cannot separate the distributions in a statistical fashion; a larger sample of ETGs may be slightly different, but we cannot separate the difference in the K-S statistic, and offer a hint that the covering fraction above log $N_{\text{H}i}$ is

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Figure 2. Ly\textsc{a} rest-frame equivalent width $W_r$ vs. impact parameter $\rho$ for our COS-Halos sample of SF (blue) and ETG (red) galaxies. Note that only 15 ETGs appear in this figure, since in one case we do not have coverage of the Ly\textsc{a} transition. Even with four low values seen in the ETGs, there is no statistically significant evidence of a dependence on galaxy type (red vs. blue).

4. THE STRONG H\textsc{i} IS BOUND TO ITS HOST GALAXY

The detected H\textsc{i} shows a strong relationship to the targeted ETGs. It is found at separations consistent with being well inside the virial radius ($R_{\text{vir}} \sim 300$ kpc), and it is closely associated with the stars in velocity space. Figure 3 shows the full velocity range of the detected H\textsc{i} absorption with respect to the systemic velocity of the galaxy’s stars (set to $v = 0$). The relative errors between absorption and galaxy redshift (i.e., between the wavelength solutions of the optical and COS spectroscopy) is $\sim 30$ km s\textsuperscript{-1}. The filled symbols mark centroid velocities of the fitted components, while the range bars show the full width at zero absorption, a measure of the greatest kinematic extent of the detected H\textsc{i}. These velocities are plotted with respect to the inferred dark matter halo mass, which is derived from the photometrically estimated stellar mass using the mean relation from Moster et al. (2010). The dashed curves show the escape velocity from the halos as a function of mass, at distances of 50, 100, and 150 kpc (from outside to inside). Nearly all the detected H\textsc{i} is found at velocities below the escape velocity. This is true even if we increase the velocity ranges by $\sqrt{3}$ to account for unconstrained projection effects (since relative Doppler shifts are a sightline-projected lower limit to the true three-dimensional space motion). It is also possible that some of the detected ionized gas is in fact bound to satellite galaxies in the vicinity of the targeted galaxy, if so, the kinematics suggest that the satellites are themselves bound and would be counted among the CGM mass budget for the host galaxy. We conclude that the detected H\textsc{i} is predominantly bound to its host galaxy, and not escaping at the time it is observed.

5. THE STRONG H\textsc{i} IS COLD COMPARED WITH HALO VIRIAL TEMPERATURES

Because COS-Halos typically covers multiple Lyman series lines at $z \gtrsim 0.2$ (Figure 1), we can often derive line-broadening parameters that are not available when relying solely on Ly\textsc{a} (which is almost always saturated). We perform profile fits to derive $N_{\text{H}i}$ and Doppler $b$ for each component, where possible. These line widths provide robust upper limits on the gas temperature under the assumption that the broadening is

\footnote{This is very likely in the two systems with log $N_{\text{H}i} > 10^{19}$.}
purely thermal, \( b = \sqrt{2kT/m_H} \). From the measured Doppler parameters (Figure 4) we can firmly establish temperature upper limits of \( T \lesssim 2 \times 10^5 \) K (\( b_{\text{therm}} < 60 \) \( \text{km s}^{-1} \)), with 80% at \( T < 10^5 \) K (\( b_{\text{therm}} = 40 \) \( \text{km s}^{-1} \)). These line widths are upper limits based on the observed profiles, and can only decrease if the observed profile turns out to be composed of narrower unresolved components, or is significantly affected by non-thermal broadening (which has been shown to be common; Thom & Chen 2008; Tripp et al. 2008).

We therefore conclude that the detected H i traces mainly “cool” (possibly photoionized) gas, at temperatures well below the \( \gtrsim 10^5 \) K virial temperatures of halos in this mass range. These temperatures resemble the expectations for the “cold mode” of galaxy gas accretion. Together with the finding that the detected gas is plentiful and bound, this finding suggests that the deposition of cold gas into galaxy halos (from the inside or the outside) and/or the formation of clouds at \( \ll T_{\text{vir}} \) are not fully quenched even in galaxies that have ceased to form stars.

6. IMPLICATIONS FOR THE CGM MASS

The total mass of cool gas in ETG halos is of interest in comparison to their stellar masses and interstellar gas reservoirs. Having measured the covering fraction and typical column density, we can estimate the detected H i mass from physical arguments and simple models. The simplest possible mass estimate comes from multiplying a surface density by an area:

\[
M_{\text{HI}} = \pi R^2 \langle N_{\text{HI}} \rangle \rho_{\text{hit}} f_{\text{hit}} \]

\[
\gtrsim 2.8 \times 10^6 \left( \frac{N_{\text{HI}}}{10^{16}} \right) \left( \frac{f_{\text{hit}}}{0.5} \right) \left( \frac{R}{150 \text{kpc}} \right)^2 M_\odot,
\]

where we have taken a typical \( N_{\text{HI}} = 10^{16} \text{ cm}^{-2} \), at which the hit rate is \( f_{\text{hit}} = 0.5 \) for ETGs, and \( \rho = 150 \text{kpc} \). This mass of H i is strictly a lower limit because we have taken the typical minimum

\[N_{\text{HI}} \text{ permitted by the profiles of saturated lines and surveyed a radius that may not encompass the full CGM mass (cf. Prochaska et al. 2011). The corresponding total mass of CGM hydrogen is } M_{\text{HI}} = M_{\text{HI}}/f_{\text{hit}}, \text{ where } f_{\text{hit}} \text{ is the typical neutral fraction in the gas. Thus the ionization correction is the major factor in setting the total mass, but the ionization conditions, and thus the total mass of the CGM gas, depend on the unknown temperature and density of the detected material. Modestly overdense gas in the CGM should be exposed to the cosmic ionizing background radiation, which will further suppress the neutral fraction and imply a much larger mass.}

To estimate what CGM masses are possible for the ETGs we show a simple halo model in Figure 5 that uses a power-law gas density profile to a uniform ionizing background and held at fixed temperature. The gas density follows a power-law dependence with radius,

\[n \propto (R/R_{\text{vir}})^{-\alpha}, \text{ with } \alpha = 2, \text{ normalized to a specific cosmic overdensity } \delta_0 \text{ at } R_{\text{vir}}.\]

The photoionization equilibrium solutions were derived using Cloudy models (Ferland et al. 1998) and including ionization by the Haardt & Madau photoionizing background (for \( z = 0.2 \)) and the temperature-dependent collisional ionization equilibrium. We neglect any photoionizing contribution from the nearby ETGs since their SFRs are not high enough to contribute significantly to the 1 Ryd background in their halos (Tumlinson et al. 2011b).

Overdensities of \( \delta_0 = 20–50 \) are required to match the ETG H i detections with \( \log N_{\text{HI}} \sim 16 \). This profile gives a total mass of \( \log M_{\text{HI}} \sim 11 \). The lower model adopts \( \delta_0 = 2 \), and is a better match to the non-detections. Note that the results depend less on the chosen temperature than on the density normalization. From these simple models we conclude that the detected CGM is consistent with a mass \( M_{\text{CGM}} \gtrsim 10^{10–11} M_\odot \). This mass is significant by comparison with the interstellar gas masses detected in other ETGs (Section 1). At the high end, these masses are potentially significant reservoirs of “missing baryons” in the budgets of these massive halos. We emphasize that these simple models are not rigorous derivations of the ionization correction.

\[\delta_0 = 50, \log M(<150 \text{kpc}) = 11.0\]

\[\delta_0 = 2, \log M(<150 \text{kpc}) = 9.6\]

Figure 4. On a component-by-component basis, the \( N_{\text{HI}} \) and Doppler b parameter for H i around ETGs. Even if we assume that there are no non-thermal contributions to the line broadening, most of the detected H i has implied temperatures of \( T \lesssim 2 \times 10^5 \) K.

(A color version of this figure is available in the online journal.)

Figure 5. \( N_{\text{HI}} \) vs. impact parameter \( \rho \) for all 16 ETGs. Lower limits are systems for which all available Lyman lines are saturated. The model profiles show two simple halo models for overdensity normalization \( \delta_{\text{up}} = 50 \) (upper pair, green) and \( \delta_{\text{up}} = 2 \) (lower pair, purple). Within each set of curves the lower curve corresponds to \( T = 10^5 \) K, while the upper bounding curves are for \( T = 10^6–10^7 \) K; these are the two relevant temperature limits from the kinematics analysis above.

The total gas masses inside 150 kpc are log \( M(<150 \text{kpc}) = 9.6–11 \).

(A color version of this figure is available in the online journal.)
from which the actual gas column densities $N$ can be inferred. We will publish separately a full analysis of the gas column densities based on models calibrated to the many available metal lines in these absorbers (Werk et al. 2012). Rather, these simple estimates show that ETGs harbor a significant mass of cold, bound gas in their CGM.

7. IMPLICATIONS

The COS-Halos survey has detected significant quantities of cool, likely photoionized gas bound to the halos of massive ETGs. The cool gas does not appear to be correlated with SF, in stark contrast with $\text{O vi}$, which is strongly dependent on the presence or absence of SF (Tumlinson et al. 2011a). The cool gas reservoir may contribute $\gtrsim 10^{9-11} M_\odot$ of gas to the halos of ETGs, comparable to the interstellar reservoirs (Section 1), and exists well below the halo virial temperatures. This material is typically well within the escape velocities of the host galaxies, so it may be re-accreted by the galaxies and eventually used for SF. The question then becomes, why does the gas not do so?

These ETGs have been quenched, in the usual sense that they are no longer forming stars. These strong $\text{H i}$ absorbers and the cool CGM they trace were predicted to disappear at the end of cold accretion, which should not operate in halos at this mass (Stewart et al. 2011). If $M_{\text{CGM}} \sim 10^{10} M_\odot$ is typical of the star-forming galaxies in COS-Halos as well as the ETGs, then the ETGs probably have less mass in their CGM relative to their stellar and halo masses than the SF galaxies (at least in cool gas). This might be the signature of quenching that can suppress but not completely remove cold gas from the halo, or that the gas can re-accrete long after quenching. It is also possible that the quenching mechanism did remove all the CGM gas, after which cold clouds re-accrete from the intergalactic medium (IGM) or re-form from thermal instabilities in the hot corona.

Models that attempt to explain the formation and evolution of ETGs will need to account for this significant budget of cold gas in their halos. While it is possible that some of this gas is the direct product of ejection by supernovae while SF was occurring, it is perhaps more likely to be gas cooled from their hot halos or falling in from the IGM. In this case, preventive feedback may act to slow its accretion, allowing only small budgets of interstellar gas to enter the interstellar medium (ISM) and form stars. Some of it (especially the stronger systems) may be bound to satellites that are themselves bound to the host, and thus present or future contributors to the diffuse CGM. In any case, our findings indicate that the quiescence of SF in ETGs generally cannot be attributed exclusively to the quenching of gas in their CGM.

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