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Ultraviolet Perspectives on Diffuse Gas in the Largest Cosmic Structures

Burchett, J.; Butsky, I.; Tremmel, M.; Bordoloi, R.; Bryan, G.; Cai, Z.; ... ; Zheng, Y.

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Ultraviolet Perspectives on Diffuse Gas in the Largest Cosmic Structures

Thematic Areas: Planetary Systems Star and Planet Formation
 Formation and Evolution of Compact Objects Cosmology and Fundamental Physics
 Stars and Stellar Evolution Resolved Stellar Populations and their Environments
 Galaxy Evolution Multi-Messenger Astronomy and Astrophysics

Principal Author:

Name: Joseph N. Burchett¹, Daisuke Nagai²

Institution: 1) Univ. of California - Santa Cruz; 2) Yale University

Email: burchett@ucolick.org; daisuke.nagai@yale.edu

Phone: +1 (831) 459-3081; +1 (203) 432-5370

Co-authors: Iryna Butsky (UW-Seattle), Michael Tremmel (Yale), Rongmon Bordoloi (NC State), Greg Bryan (Columbia), Zheng Cai (UCSC), Rebecca Canning (Stanford), Hsiao-Wen Chen (U. Chicago), Alison Coil (UCSD), Drummond Fielding (Flatiron Institute), Michele Fumagalli (Durham), Sean D. Johnson (Princeton), Vikram Khaire (UCSB), Khee-Gan Lee (Kavli IPMU), Nicolas Lehner (U. Notre Dame), Nir Mandelker (Yale/Heidelberg), John O’Meara (Keck Observatory), Sowgat Muzahid (Leiden), Dylan Nelson (MPA), Benjamin D. Oppenheimer (CU-Boulder), Marc Postman (STScI), Molly S. Peeples (STScI/JHU), Thomas Quinn (UW-Seattle), Marc Rafelski (STScI/JHU), Joseph Ribaldo (Utica College), Kate Rubin (San Diego State), Jonathan Stern (Northwestern), Nicolas Tejos (PUCV), Stephanie Tonnesen (Flatiron Institute), Todd Tripp (UMass-Amherst), Q. Daniel Wang (UMass-Amherst), Christopher N. A. Willmer (Steward Observatory), Yong Zheng (UC Berkeley)

Abstract: The past decade has seen an explosion of discoveries and new insights into the diffuse gas within galaxies, galaxy clusters, and the filaments composing the Cosmic Web. A new decade will bring fresh opportunities to further this progress towards developing a comprehensive view of the composition, thermal state, and physical processes of diffuse gas in the Universe. Ultraviolet (UV) spectroscopy, probing diffuse $10^4 - 10^6$ K gas at high spectral resolution, is uniquely poised to (1) witness environmental galaxy quenching processes in action, such as strangulation and tidal- and ram-pressure stripping, (2) directly account for the baryon content of galaxy clusters in the cold-warm ($T < 10^6$ K) gas, (3) determine the phase structure and kinematics of gas participating in the equilibrium-regulating exchange of energy at the cores of galaxy clusters, and (4) map cold streams and filaments of the Cosmic Web that feed galaxies and clusters. With a substantial UV undertaking beyond the Hubble Space Telescope, all of the above would be achievable *over the entire epoch of galaxy cluster formation*. Such capabilities, coupled with already-planned advancements at other wavelengths, will transform extragalactic astronomy by revealing the dominant formation and growth mechanisms of gaseous halos over the mass spectrum, settling the debate between

early- and late-time metal enrichment scenarios, and revealing how the ecosystems in which galaxies reside ultimately facilitate their demise.

1 UV Frontiers: The CGM to Galaxy Clusters & Cosmic Web

Enormous progress has been made over the last decade in our understanding of the diffuse gas within the circumgalactic medium (CGM), intracluster medium (ICM), and intergalactic medium (IGM) in the Cosmic Web. Ultraviolet (UV) spectroscopy has been the primary driving force behind advancements in the CGM, while X-ray and radio techniques have predominantly been employed for groups and clusters of galaxies. A new decade brings fresh opportunities to build on this multiwavelength progress towards unraveling the composition, thermal state, and physical processes within the most massive structures in the Universe, which bear directly on galaxy evolution, structure formation, and cosmology.

The CGM is a critical piece of the ecosystems within which galaxies live, breathe, and die (see White Paper by Peebles et al.). We have seen a progression from detecting/confirming/characterizing the presence and composition of the CGM [1–5] to leveraging diagnostics from larger datasets and informing rigorous theoretical pursuit of the intimate connection between galaxy evolution and the CGM [6–12]. Among the notable CGM discoveries are (1) the CGM around star-forming galaxies is abundant in the gas traced by O VI while the CGM of quiescent galaxies is deficient [13, 14], (2) the cool and warm-hot phases of the CGM potentially comprise enough mass to solve the ‘missing baryons’ problem on galaxy scales [for L^* galaxies; 15, 16], and (3) the cool gas contents of the CGM are highly dependent on the galaxy environment [14, 17–19]. These advances have all come through UV absorption line spectroscopy of background QSOs. Particularly aided by the sensitivity of the Cosmic Origins Spectrograph (COS) aboard *Hubble Space Telescope* (*HST*), we are now able to design absorption line experiments focusing on particular classes of galaxies, e.g., L^* galaxies [20], dwarfs [18, 21, 22], and luminous red galaxies [23–25].

UV astronomy is poised to bring a unique but critical perspective to diffuse gas physics, from galaxies to galaxy clusters and the Cosmic Web, through the combination of (a) exclusive access to spectral transitions from cool (10^4 K) to warm ($10^5 - 10^6$ K) gas and (b) unrivaled spectral resolution capability for the physical processes of interest. Some progress has been made to apply similar approaches to more massive structures, such as galaxy clusters and large scale filaments and voids [e.g., 19, 26–29], but this body of work is decidedly much less mature. Progress is partly hindered by the fact that massive halos are rarer than less massive halos. This scarcity, coupled with the underlying paucity of viable UV-bright background sources such as QSOs, have limited the feasibility of building large statistical samples.

Although focused efforts with *HST/COS* can make great strides in setting benchmarks for cosmological hydrodynamical models, more advanced space-borne UV-sensitive assets, such as the Large Ultraviolet Optical Infrared [*LUVOIR*; 30] observatory, stand to bring about a revolution in our understanding of gas flows, enrichment, and ultimately galaxy evolution on the largest scales. As currently planned, *LUVOIR*’s 15m aperture will provide a factor of 50 increase in collecting area over *HST*, and improvements in detector and mirror coating technology will boost throughput dramatically and to broader wavelength coverage. In addition, multi-object spectroscopy [31] via a micro-shutter array will provide integral field spectroscopy over a $3' \times 3'$ field of view. The monumental increase in sensitivity provided by *LUVOIR* translates into two key practical observational implications: (1) the number density of background sources feasibly observed for absorption line spectroscopy increases by > 3 orders of magnitude and (2) sources for which we can readily obtain signal-to-noise ratio (S/N) of ~ 10 with *HST/COS* may yield $S/N > 50$ with similar integration times. In this White Paper, we highlight key science cases where UV spectroscopy

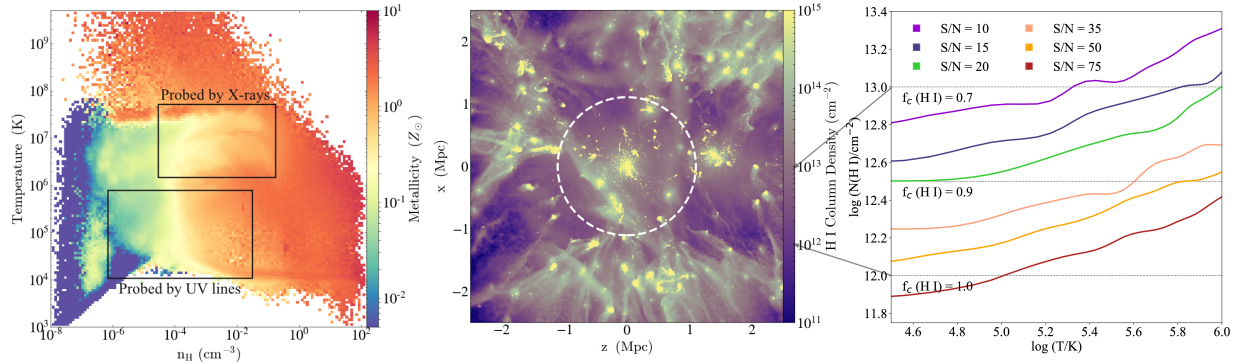


Figure 1: Properties of the cold-warm gas in the RomulusC high-resolution galaxy cluster simulation, with a mass of $M_{200} = 10^{14} M_{\odot}$ at redshift $z = 0.3$. *Left*: The mass-weighted metallicity in bins of temperature and density. Indicated are the regimes of phase space for which X-ray and UV observations are sensitive. While the gas probed by X-rays is of nearly uniform enrichment, that probed by the UV exhibits a much wider range of metallicity. *Center*: A projection of the predicted HI column density distribution (integration depth 5 Mpc). The dashed white circle denotes R_{200} . Diffuse gas readily probed by UV spectroscopy is pervasive throughout the cluster, particularly towards the outskirts. *Right*: Column density detection limits of UV HI Lyman- α lines as a function of temperature assuming the lines are thermally broadened. The curves correspond to different S/N levels ranging from those often obtained with *HST/COS* (S/N \sim 10-15) to those readily achievable with an advanced UV mission such as the 15-m *LUVOIR* (S/N \sim 50-75). Covering fraction predictions from RomulusC corresponding to 3 column density limits are marked with horizontal dotted lines on the right; two are connected to their corresponding shading in the map on the left. The next generation of UV telescopes will use HI in absorption to uncover the galaxy cluster structures invisible to X-rays.

will provide unique insights into the most massive structures in the Universe, and we discuss how current (*HST/COS*) and future (*LUVOIR*) missions can deliver transformative understanding of galaxy evolution, galaxy cluster physics, and gas within the Cosmic Web.

2 Galaxy Clusters: a new frontier at all wavelengths

CGM stripping and chemical enrichment in galaxy clusters: Galaxy clusters form at the nodes of the cosmic web and are the densest pockets of the Universe. Recent multiwavelength observations (ranging from microwave to optical and X-ray) of galaxy clusters provide unprecedented views of the distribution of dark matter, gas and stars, enabling a plethora of new insights into the physics of both cluster cores [e.g., 32] and outskirts [33]. The outskirts of galaxy clusters mark an exciting new territory for understanding how the clusters connect to the cosmic web, and they offer a powerful laboratory for studying the properties of the X-ray emitting ICM, chemical enrichment processes of the ICM, and evolution of galaxies in dense environments. However, the cold-warm gas in cluster outskirts and around infalling galaxies remains elusive and largely unexplored.

Modern cosmological simulations predict that the relative fraction of 10^{4-6} K gas greatly increases beyond the cluster virial radius [Butsky et al., in prep; 34], as also expected given evidence for a shock at $\sim R_{\text{vir}}$ in SZ data [35]. UV absorption line surveys of cluster outskirts could discern between competing models, which vary in predicting how quickly these cool/warm gas fractions rise and how far into the outskirts they begin to exceed the hot gas. The cold-warm gas properties in cluster outskirts are especially important, because they contain crucial information about how the metal-rich CGM of infalling cluster galaxies are stripped and subsequently pollute the chemical content of the ICM [36–41]. As such, further studies of the cold-warm gas in galaxy clusters promise new insights into the following: *Where and how is the CGM of infalling galaxies*

stripped through interactions with the ICM? What quenching mechanisms are most important in high density environments? How do metals spread in the ICM? What is the role of feedback on the thermodynamic and chemical properties of the CGM and IGM?

UV spectroscopy can bring a novel perspective to the cold-warm gas in galaxy clusters. Figure 1 shows an H I column density map from the high resolution galaxy cluster simulation RomulusC [Butsky et al., in prep; 42]. H I is clearly abundant throughout the cluster at column densities that are near the detection limits for $S/N \sim 10$ spectra, which are relative routine for *HST/COS* observing QSOs with $m_{FUV} \lesssim 19$. At these brightnesses, one can feasibly construct samples of background QSO/foreground cluster pairs. Indeed, the few studies targeting clusters with QSO sightlines generally show a comparable detection rate of H I [19, 26, 43]. However, there appears to be a dearth of H I absorbers at small velocity separation from the cluster redshift and at very small impact parameters, suggesting that the gas in the very inner regions is more highly ionized.

Early observational evidence indicates stark differences between the CGM of cluster and field galaxies. For example, the CGM of cluster galaxies are highly depleted, with an H I covering fraction of 25% versus nearly 100% for field galaxies [19], illustrating increasing environmental influence on the composition, kinematics, and ionization state of the CGM [18, 44–47]. A large sample of QSO sightlines probing clusters, coupled with follow-up galaxy spectroscopy, can make a good deal of progress in determining where upon infall and to what degree galaxies are stripped. Such experiments will also inform how the stripping of cluster galaxies contributes to the multi-phase structure and metal content of the ICM on all scales.

Beyond their high sensitivity to the diffuse gas, another huge advantage of UV techniques to this field is their *high spectral resolution*. The highest resolution modes of COS reach FWHM ~ 18 km/s. With the resolution achievable in the UV, and given sufficient S/N, individual low-column density cool clouds (with narrow line profiles) will be easily distinguishable from warmer clouds with broad profiles. UV constraints on the kinematic properties of stripped CGM in galaxy clusters will be highly complementary to the bulk and turbulent gas motions of the hot ICM, which will be provided by ongoing and upcoming high-resolution X-ray (e.g., *XRISM*, *Athena*, *Lynx*) and SZ spectral imaging observatories (e.g., *CCAT-prime*, *NIKA2*, *MUSTANG2*, *TolTEC*, *AtLAST*, *LST*, *CSST*, *CMB-in-HD*) in the coming decade [48, 49, for recent reviews].

Formation and evolution of cluster cores over cosmic time: Progress has also begun in quantifying the cold gas contents of clusters in their infancy. The left-panel of Figure 2 shows a > 400 kpc $\text{Ly}\alpha$ nebula, which also exhibits extended C IV and He II emission, in a $z = 2.3$ protocluster discovered using narrowband imaging and slit spectroscopy [50]. A large > 100 kpc $\text{Ly}\alpha$ nebulae in the core of an X-ray emitting galaxy cluster at $z = 1.99$ has also been detected [51]. The presence of such material, particularly in the core of such a massive virialized halo (and observed on smaller scales at $z \sim 0$ [52, 53]), poses important questions as to its origins: *Are streams of gas readily able to penetrate deep into these massive halos, potentially providing fuel for star formation in the resident galaxies at high redshift [54, 55]? Are we witnessing condensation directly out of the hot cluster atmosphere at early times, perhaps taking part in a self-regulating feedback process that feeds AGN activity and in turn injects energy into the surrounding CGM and ICM [56]?*

These recent discoveries described above point towards a broader opportunity to track the evolution of galaxy clusters from the early protocluster phase through the mature ecosystems we observe at present times. Figure 2 (right) shows one prediction of the evolving mass fraction of 10^4 , 10^{5-6} , and $> 10^6$ K gas in a simulated cluster. While much is to be learned at $z > 2$, empirically

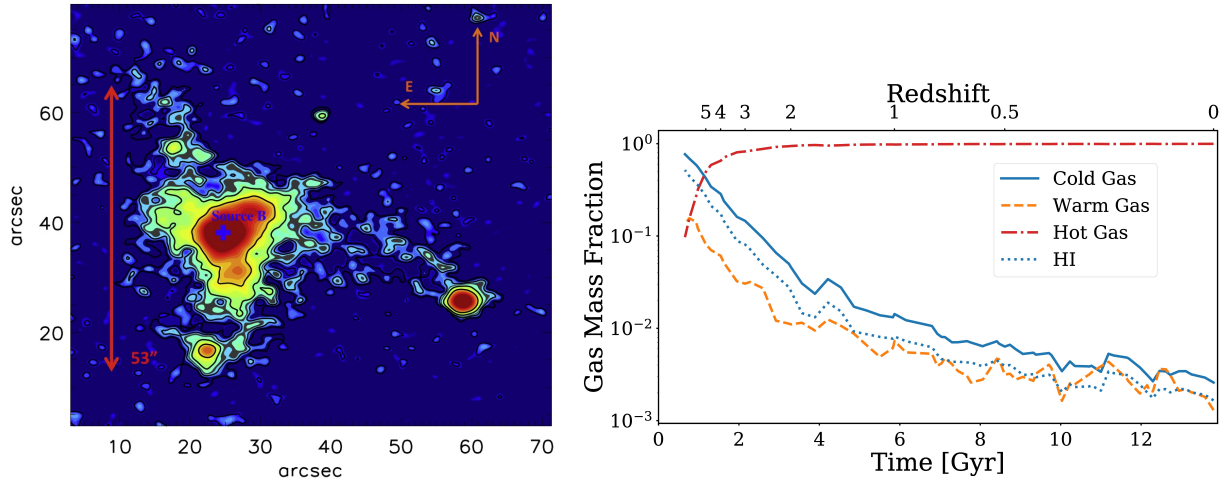


Figure 2: *Left:* A > 400 kpc enormous $\text{Ly}\alpha$ nebula discovered within a $z = 2.3$ protocluster [50], revealing a large reservoir of cold gas in the early stages of cluster formation. *Right:* The redshift evolution of 10^4 (cold), 10^{5-6} (warm), and $> 10^6$ K (hot) gas mass fractions within R_{200} of the RomulusC simulated galaxy cluster. The temperature distribution in clusters changes dramatically with redshift at $z \gtrsim 2$. Systematically pursuing observations of $\text{Ly}\alpha$ and metal line-emitting nebulae (left panel) will place rigid constraints on the evolution of the ICM and cluster members.

constraining this evolution to any later times using ground-based instrumentation has already run into the unforgivingly hard wall of the UV atmospheric cutoff. A space-based observatory with integral field spectroscopic capability, such as the Large UV Multi-Object Spectrograph [LUMOS; 31] micro-shutter array aboard *LUVOIR*, or a balloon-borne experiment like FIREBall [57] could image the UV line-emitting diffuse gas *and measure the kinematics* within clusters all the way to $z \sim 2$, where telescopes on the ground can take over. The cool-warm gas constraints provided by rest-frame UV transitions, such as $\text{Ly}\alpha$, C IV, and He II already observed at $z \gtrsim 2$, will provide benchmarks across cosmic time for cluster formation models.

3 The Cosmic Web

On cosmic, several novel methods have been employed to attempt mapping gas in the filaments, sheets, and voids composing the Cosmic Web, including stacking the SZ effect signal between massive halos [59, 60], $\text{Ly}\alpha$ absorber statistics [28, 61], and $\text{Ly}\alpha$ forest tomography [62, 63]. We focus on this last method to highlight prospects for studying the Cosmic Web given potential upcoming UV capability. Figure 3 shows a reconstructed map of Cosmic Web structure traced by $\text{Ly}\alpha$ forest absorption in ground-based spectra of background star forming galaxies. By using background galaxies instead of quasars, the CLAMATO project increased the projected sightline density from 80 deg^{-2} to 1500 deg^{-2} . Such sightline densities would be possible for $z < 2$ (recall the hard redshift limit for ground-based $\text{Ly}\alpha$ surveys) under the current *LUVOIR* specifications, with the added efficiency of multi-object spectroscopy for simultaneously observing multiple sightlines.

Lastly, filaments in the Cosmic Web have been of extremely high interest due to their purportedly housing the bulk of "missing baryons" in the form of warm-hot (10^{5-6}K) intergalactic medium [WHIM; e.g., 64–66]. In addition to broad $\text{Ly}\alpha$ features, the extreme UV provides a relatively robust tracer of the WHIM in the Ne VIII 770, 780 Å doublet. The precipitous decline in *HST*'s sensitivity below 1150 Å renders Ne VIII features effectively unreachable at $z < 0.5$.

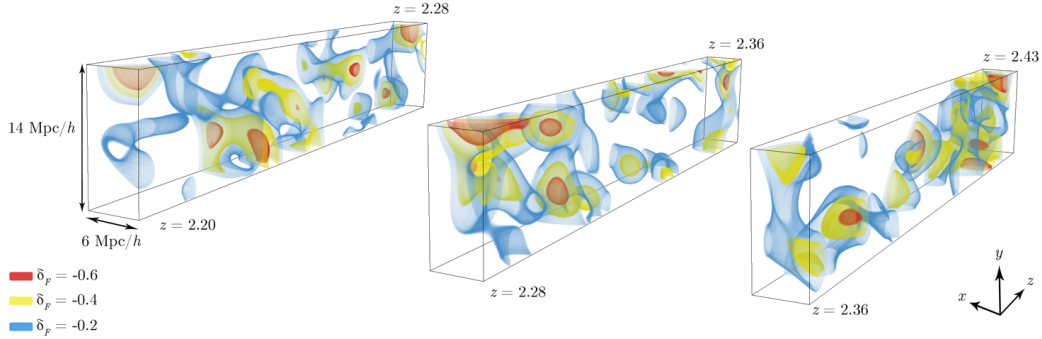


Figure 3: A tomographic map of filaments and voids in the Cosmic Web reconstructed from Ly α absorption at $z > 2$ against background galaxies [58]. Colors represent Ly α transmission, with red regions corresponding to the most overdense regions inferred from Ly α absorption. The CLAMATO team achieved a high density of sightlines through this volume by leveraging relatively faint galaxies as background sources rather than QSOs. Even higher sightline density may be achieved down to $z = 0$ by coupling this technique with a large aperture UV facility.

Furthermore, Ne VIII features that trace the low density WHIM are expected to be very weak [67]. Herein lies a prime opportunity for future space-based missions: by providing decent throughput below 1000 Å, they enable galaxy surveys sufficiently wide and deep to map out the large scale galaxy distribution and, e.g., separate circumgalactic Ne VIII [19] from truly intergalactic material.

4 Prospects for the Next Decade

Here, we summarize the resources that can be leveraged now with *HST/COS* and in the future with the *LUVOIR* observatory as currently conceived.

HST/COS: Large surveys of cluster/QSO sightline pairs can provide a census of the cool-warm gas contents of galaxies, their outskirts, and pre-accretion shock region. High spectral resolution $\delta v \sim 20$ km/s enables kinematic separation of physically distinct cool, narrow-line absorption components and warm, broad-line components, which can in turn help identify bulk flows and kinematically connect absorbers to galaxies undergoing gas stripping within the cluster.

LUVOIR: A factor of > 50 in sensitivity over *HST* means the ability to (1) obtain extremely high S/N (> 50) in the same amount of time for the same sources we observe now with *HST* and (2) feasibly observe > 1000 background sources per square degree on the sky. Assuming a cluster with $M_{200} = 10^{14} M_{\odot}$ at $z = 0.3$, this source density translates to $\gtrsim 16$ potential background sources for *any* cluster with at least this mass being observable for absorption studies. The increased sensitivity plus wavelength coverage down to 1000 Å will provide a full suite of metal line diagnostics from low-, mid-, and high-ionization species to enable detailed modeling of the physical conditions of gas in any environment. Integral field spectroscopic capability will enable imaging the diffuse gas emission [68, 69], e.g., resolving its geometry and kinematics.

UV spectroscopy provides unique insights into the cold-warm gas in and around most massive structures in the Universe, providing highly complementary views of the baryonic contents of the universe provided by X-ray and microwave observations (see white papers on these topics). When taken together, these forthcoming multiwavelength observations will provide a comprehensive view of the gaseous composition and processes in the Universe and deliver transformative understanding of galaxy evolution, galaxy cluster physics, and gas within the Cosmic Web.

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