SCIENCE FROM IGM/CGM EMISSION MAPPING

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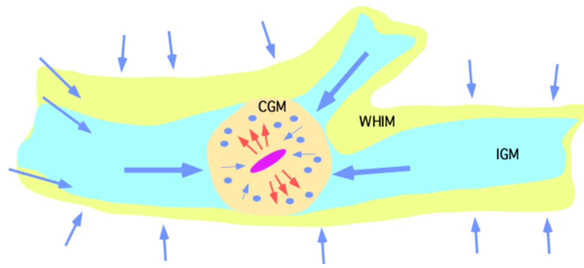
PROBING BARYONIC STRUCTURE FORMATION USING IGM MAPPING

NASA Balloons and Explorers [1, 2] have opened an age of precision cosmology by mapping the Cosmic Microwave Background. At the same time the processes that built cosmic structure and the galaxies that trace it are unknown. Models predict that the dark matter seeded by primordial quantum fluctuations formed the architecture of the Universe, a "cosmic web" of sheets and filaments of dark and normal (baryonic) matter. As the Universe expands, denser regions of dark matter collapse to form "dark halos", becoming much denser than average (and therefore characterized by the "overdensity parameter" δ the local density normalized by the average cosmic density). Dark halos have δ~200, and the dark matter cannot further collapse because it has no way to release gravitational energy. A fraction of the baryonic matter falls into these halos out of the cosmic web, fueling the formation and growth of galaxies over time. In order to form galaxies, baryonic matter must condense by more than 10 million times further, an extraordinary transformation that is extremely difficult to model with equations or even with large computer simulations, because of the complexity of the processes involved. Baryons, unlike dark matter, can convert the gravitational energy gained in this collapse from heat to cooling radiation. They must do so to collapse further, but this formative process is complex.



	Component			
Property	**Cosmic Web**	**Web/ Halos**	**Dark Halos**	**Galaxies**
Baryon & structure tracer	IGM *fuel*	WHIM *baryons metals*	CGM *infall winds metals*	*XUV disk gal. winds, SF*
δ	1-100	1-100	10^2-10^5	>10^6
Size [Mpc]	0.3-30	1-30	0.1-0.3	0.03-0.1
T[K]	10^4-10^5	10^5-10^7	10^4-10^6	
QSO absorption	Lα forest	OVI, broad Lα	Ly limit Metal lines	Damped Lα
Emission	Photon pumping (PP)	Collisional excitation (CE), PP	CE, PP,Lα fluorescence	UV cont CE from feed-back
Intensity [LU]	1-100	1-100	10^2-10^4	

Figure 1: *IGM/CGM emission probes all these components of the IGM, yet to be mapped.*

Baryons forming and fueling galaxies continue their catastrophic collapse by another 6-10 orders of magnitude to form molecular clouds and a further 12 orders of magnitude to become stars. These remarkable events, while complex, at least have a long history of study using a cornucopia of observational probes. The most massive stars formed produce energetic stellar winds and supernova explosions, which inject energy and heavy elements formed by fusion in their cores back into the galaxy's interstellar medium (ISM), the galaxy's halo, and the surrounding IGM. These "feedback" processes are very poorly understood, and may even control the infall of new fuel, yet they are essential to models that correctly predict fundamental properties such as the size, angular momentum, and luminosity function of galaxies and the physical connection between galaxy and dark halo properties.

Observers primarily use large galaxy surveys for mapping structure and galaxy evolution at low and high redshift. But galaxies represent less than 1% of the mass and only 10-20% of the baryons! The IGM hosts the majority of baryons, and plays a central role in the growth of structure and the evolution of galaxies. Yet our view of the IGM is based largely on the powerful but restricted information from QSO absorption line studies.

A Tour of the IGM. We summarize the physical components of the IGM, their relationship to galaxies, and their observational signatures in Figure 1. The picture we paint is inferred from QSO absorption line spectra (see [3] for a recent census), but has never been demonstrated with emission maps.

IGM and WHIM: Most of the web is moderate overdensity ($1<\delta<100$) gas ionized by the metagalactic UV background (UVB), and continuing to expand with the Hubble flow. Trace HI in the cosmic web is responsible for the Lyman α "forest" observed in QSO absorption line spectra. The forest is a powerful constraint on large-scale structure and cosmology, since simulations show that IGM baryons trace dark matter. There are metals in the cosmic web, suggesting early and on-going enrichment by galactic winds. At z=0 we suspect most baryons have collapsed into a Warm-Hot Intergalactic Medium (WHIM, $T_{vir}\sim10^5$-10^7K,) which produces weak, broad, difficult to detect Lyα absorption, and most of the z~0 OVI absorption.

CGM: Galaxies and groups form in dark matter halos ($\delta>100$) that form in the denser parts of web filaments and their intersections. We call the uncollapsed gas in halos the "Circum-Galactic Medium" (CGM). This gas may be infalling from filaments, cooling and collapsing onto the galaxy to fuel on-going star formation, stripped from merging subunits, or ejected and heated by galactic winds. CGM gas produces Lyman limit absorbers ($N_{HI}>10^{18}$ cm^{-2}), metal line absorbers (MgII, CIV, some OVI), and possibly Damped Lyα systems (DLA; $N_{HI}>10^{20}$ cm^{-2}).

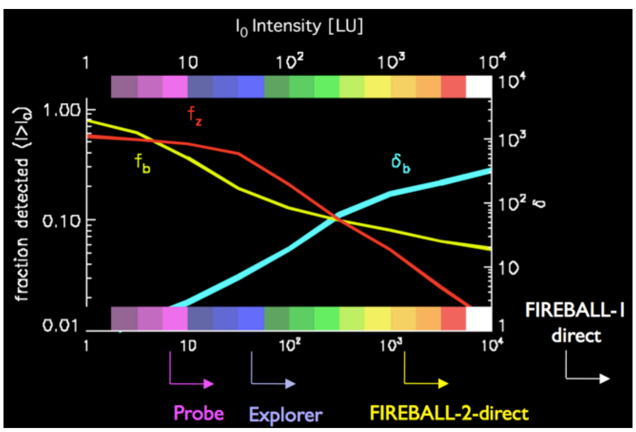


Figure 2. Estimated IGM Lyα emission line intensity vs. baryon overdensity δ_b (cyan curve). Fraction of baryons with Lyα intensity above I_0 (f_b: yellow curve), and fraction of metals with OVI1033 line intensity above I_0 (f_z: red curve). Intensity color scale is same as shown in Figure 3 and 4. Limits for direct detection also shown.

Need for IGM Mapping There has been a long and productive effort to probe the IGM using QSO absorption lines and in X-ray emission in clusters. But the diffuse IGM that spans the vast majority of cosmic space, and the CGM occupying dark halos at the interface of galaxies and the IGM, remain invisible except in the shadow of sparsely distributed QSOs. There is growing evidence, from absorption line studies and from models, for a fundamental coupling of galaxies and the IGM, and the power of the IGM to probe cosmology. There is a compelling need to invent a new tool to explore the Universe, to discover and map emission from the IGM.

Emission from the IGM and CGM, while tenuous, can and will be detected by space-based spectrometers. In Figure 2 we show how the intensity of Lyα scales with overdensity δ, a good redshift-independent predictor of intensity. We also expect to detect OVI1033, CIV1549, and several other strong metal line species in CGM and WHIM. The physics of the predictions, particularly for the IGM, is straightforward and robust.

The Role of IGM/CGM Emission Mapping in Understanding Baryonic Structure Formation: First IGM Emission Measurements

The overarching question that can be addressed by IGM emission mapping is fundamental: ***"How does baryonic matter collapse, cool, form and fuel galaxies over cosmic time?"*** While the road to this answer may be tortuous, IGM emission mapping will provide a new perspective that could lead to fundamental breakthroughs by addressing these questions:

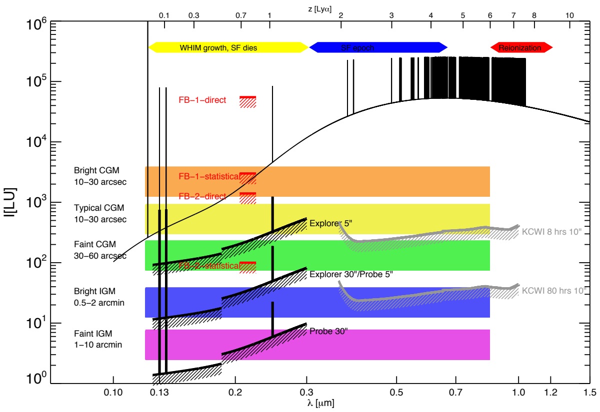


Figure 3: *Typical emission line strengths for Lyα from the CGM and the IGM. Bands show IGM emission levels, red: bright CGM, yellow: typical CGM, green: faint CGM, bright filaments, pink: faint filaments. Black curve shows typical sky background. Hatched lines show typical sensitivities for a range of feature size and exposure for UV experiments such as FIREBALL (red); Explorers and Probe-class missions (black).*

How strong is IGM emission, what is its relationship with absorption, and can emission mapping offer a new and powerful cosmological tool? The potential of IGM mapping can only be settled by detecting the emission, establishing its origin in the IGM and CGM (in contrast to star forming galaxies), and determining the typical emission strengths in various regimes. Detection and mapping require *excellent diffuse sensitivity* that is likely only obtained from dedicated instruments and/or missions. It is possible the first detections and preliminary characterization will come from Balloon and/or Explorer class missions with survey sensitivities of ~100-1000 LU over ~5 arcsec scales. Detailed mapping of multiple metal lines over a large cosmic volume will require the ~10-100 LU sensitivities of a Probe or even flagship mission instrument, which can also be used to detect and map the most diffuse filaments of the cosmic web. The fainter (~10-100 LU) but more extended (~30 arcsec) emission from filaments may also be detected by statistical means (stacking and/or cross-correlation with large-scale structure traced by galaxies) using surveys of narrowband 2D-imaging- and multi-object spectroscopy.

What is the total baryon content of the dark matter halos hosting galaxies in a 10^4-10^6K phase, and how does this gas content vary with redshift, galaxy type, evolutionary stage, and halo mass and environment? How does gas flow from the IGM into the CGM, and ultimately into galaxies to fuel ongoing galaxy formation, evolution and star formation? How do galaxies feed matter, energy, and metals back into the CGM, possibly regulating inflow and cooling? These are the missing links between the evolution of the IGM, dark halos and galaxies. There is exciting evidence from absorption line studies that extended zones of hydrogen and metals around galaxies exist [4, 5, 6, 7]. But there are almost no observational constraints on how CGM gas reservoirs are linked to the accretion of gas that fuels new star formation. We have no true maps, although there is tantalizing evidence for emission from CGM gas from Lyman Break Galaxies at z~1-3 [e.g., 8, 9] at levels of 10,000-50,000 LU. The as yet undetectable flow of baryonic matter from the cosmic web into galaxies may have been responsible for the epoch of star formation over 1<z<4. A major objective of IGM/CGM emission detection and mapping is to determine, by comparison with CGM emission at higher and lower redshift, whether the cessation of the delivery of fresh fuel explains the catastrophic fall in cosmic SFR in recent times.

How much CGM gas is inflowing to the galaxies, outflowing due to winds or AGN, replenished by inflow from the IGM? Do these gas flows regulate SF history, or are they regulated by star formation?

Map inflows. While CGM physics is more complex than IGM physics, the emission is brighter. Modern simulations have the mass and spatial resolution to trace the flow of mass and energy on scales that can resolve the CGM, but the models are in desperate need of observational input. We can compare the observed distributions of the various lines to CGM models with different assumptions. One goal is to determine the rate at which gas in the halo reservoir is accreting onto the central galaxies. By observing cooling radiation in IGM emission lines, we can detect mass fluxes as low as ~1$M_\odot$ yr^{-1}, a level that can strongly impact the evolutionary path of galaxies.

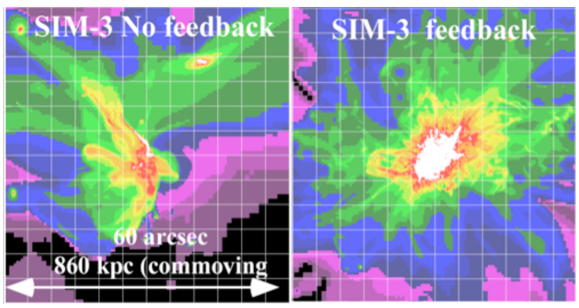


Figure 4: *Feedback has a profound effect on Lyα emission z~0.7 from the CGM. See Fig. 3 for intensity vs. color code. Grid shows typical pixel size (5") for possible UV integral field spectrometers. Simulation from Greg Bryan, Columbia University.*

Map outflows. One of the central missing elements in galaxy evolution models is an accurate physical understanding of the effects of stellar and AGN feedback. Feedback causes mass and energy to flow out of galaxies and into the CGM, driving CGM gas from one phase to another, modifying cooling times and inflow mass flux and enriching the CGM. Feedback is constantly invoked to solve outstanding problems in galaxy formation theory [e.g., 10]. Galactic winds at z~3 must have a profound impact, since every solar mass of stars formed results in a comparable mass ejected into the CGM at 500-1000 km/s! Over a 10^8 year lifespan a typical starburst galaxy will deposit $10^{59.5}$ ergs into the surrounding medium, out to hundreds of kiloparsecs. Rest UV emission sensitively maps radiative shocks and multiphase gas, and probes the flow of gas, energy, and metals into the CGM. If only 1% of the wind energy is radiated in the UV, CGM regions will glow with a Lyα intensity of 1000LU. Feedback produces profound differences in the CGM emission morphology and kinematics (Figure 4). CGM emission mapping with velocity resolution ~60 km/s will measure CGM velocity dispersion and kinematic profiles, crucial for distinguishing inflows from outflows. Outflows will be probed by making controlled comparisons between the halos of similar masses with different galaxy SFR.

Science Measurement Requirements for IGM/CGM Emission Mapping

To achieve these objectives, IGM/CGM emission mapping requires diffuse **UV sensitivity**, 5-200LU **[R1; see Table 1]** to discover and map IGM/WHIM emission that probes a significant fraction of IGM baryons in the diffuse cosmic web **[O1]**. In order to discover and map CGM emission **[O2]** in Lyα, sensitivities of 100-5000LU are required. To detect and map metal lines such as CIV1549Å, OVI1033Å, CIII977Å, etc., sensitivities of 10-500LU are needed**.**

Mapping requires **imaging spectra of 2D regions [R2a]**. 3D maps (2 spatial x 1 redshift) of IGM emission are needed to assess size, density, mass, luminosity, and other key physical parameters of the IGM **[O1, O2]**, and to disentangle the spatial and physical relationships between the IGM, galaxies, and QSOs **[O1-O3]**.

IGM/CGM emission mapping also requires **multi-object spectroscopy [R2b]** in order to survey IGM filaments over their typical sizes **[O1]**, to obtain a statistically robust sample of CGM regions **[O2]**, and to provide a robust set of integrated galaxy spectra to relate to 2D IFS spectra. We require 2D spectroscopy surveys that **sample a large cosmic volume** >10,000 Mpc^3 **[R3],** ideally in a few contiguous fields, in order to map a representative sample of 10's of IGM/CGM emission regions with cosmic variance <30% in the baryon measurement. Multi-object surveys are required to probe x10 larger volumes (>100,000 Mpc^3 **[R3]**) in order to survey enough CGM regions to connect CGM to galaxy/halo physical properties (e.g., galaxy stellar, gas, and halo mass, star formation rate, and morphological type) in a statistically robust way.

It is essential to observe hydrogen and metal resonance lines (Lyα, OVI1033, CIV1550, CIII977, etc.) simultaneously to derive line diagnostics over a **broad redshift range (0.05<z<1.5) [R4]** to map IGM, CGM and the circum-QSO medium (CQM) during the epoch of cosmic star formation (z~1) and to provide a local baseline **[O1-3]**. Emission lines observed in CGM regions with complementary absorption line probes will provide even stronger diagnostics of the phase and filling factor of the halo gas. **Velocity resolution** of 50-100 km/s [**R5]** is required to obtain velocity profiles and sufficient centroid accuracy for kinematic mapping of inflows and outflows **[O2bc]**, and optimal detection of IGM emission **[O1bc]** separated from foreground continuum and line emission from the earth and Galactic ISM. Similarly, the **spatial resolution [R6]** we require to map CGM components and distinguish them from the central galaxies (5-35 kpc physical scales, 0.2<z<1.2) **[O23bc],** is accomplished with a 2D angular resolution of 1-5 arcsec.

UV emission-line mapping can obtain optimal, sky-limited diffuse emission-line sensitivity (**R1**) given **excellent rejection of unwanted signal.** Contrasts for IGM/CGM emission signals are typically 1-30% of Solar System and Galactic ISM foregrounds (zodiacal light, diffuse Galactic light, molecular hydrogen fluorescence, high ionization ISM emission).

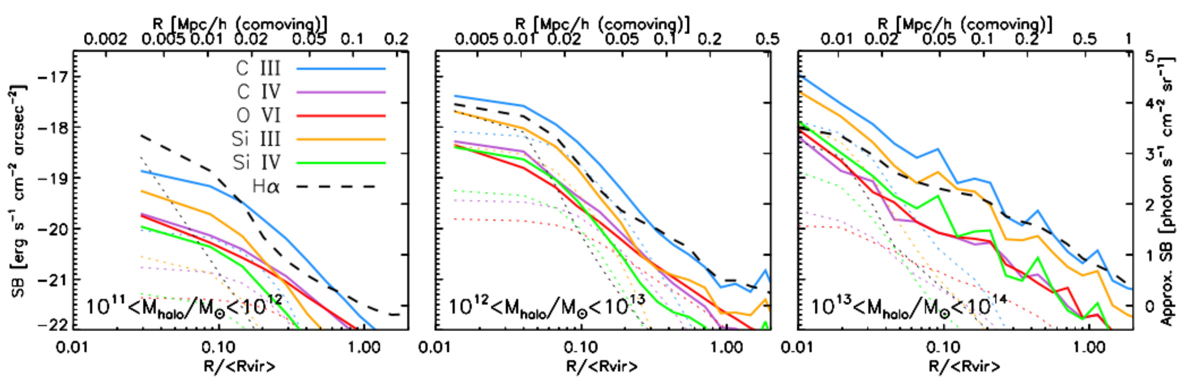


Figure 5. Metal line predictions for typical CGM regions at z=0.25 [van der Voort and Schaye, 2012; ref. 11]. *Three panels show three halo masses, profiles ranging from 0.01-1.0 of the virial radius. Detecting and mapping multiple metal lines will require sensitivities ~10-100LU on ~1-5 arcsec scales. Very faint emission at outer radii can possibly be detected using imaging spectroscopy and radial binning.*

Table 1. IGM/WHIM/CGM Emission Science Goals and Requirements

NASA Science Goal	**N1.** Understand the many phenomena and processes associated with galaxy, stellar, and planetary system formation and evolution from the earliest epochs to today.	**N2.** Understand the origin and destiny of the Universe, and the nature of black holes, dark energy, dark matter, and gravity
New Worlds New Horizons Key Science Question	**A1.** How do baryons cycle in and out of galaxies and what do they do while they are there? **A2.** What are the flows of matter and energy in the circumgalactic medium?	**A3.** How do cosmic structures form and evolve? **A4.** What are the connections between dark and luminous matter?

IGM Emission Roadmap	**Discovery and Preliminary Characterization of Emission from the IGM, WHIM, CGM, CQM**	**Physical Properties of the IGM, WHIM, CGM, CQM**	**Tracing Baryon Structure Formation using IGM and CGM Emission**
Map IGM/WHIM [N1, N2, A3, A4]	**O1a. Discover IGM emission** from the hidden baryons in the Universe. Preliminary mass census.	**O1b. Characterize IGM emission** from the hidden baryons in the Universe. Mass census.	**O1c. Exploit IGM emission** to map baryonic structure formation in cosmic web
Map CGM [N1, A1, A2]	**O2a. Discover CGM emission** to explore IGM-galaxy co-evolution	**O2b. Characterize CGM emission** to determine physical conditions, gas flows and reservoirs	**O2c. Deep, multi-object surveys of galaxy/CGM emission regions** to explain IGM-galaxy co-evolution
Map Circum-QSO Medium (CQM) [N1, N2, A1-A4]	**O3a. Discover CQM emission** to explore QSO gas environment.	**O3b. Characterize CQM emission** to determine physical properties of QSO gas environment.	**O3c. Deep maps of multiple QSO CQM reqions** to determine how QSOs are formed and evolved, and in what environments.
Surveys	**Moderately deep imaging and multi-object spectroscopic surveys** of 10-100s of halos/galaxies and filaments.	**Very deep imaging and multi-object spectroscopic surveys** of 10-100's of objects and filaments.	**Wide, deep imaging and multi-object surveys** of 100-1000's of halos, filaments, and regions.
R1. Diffuse UV sensitivity: (LU = ph cm^{-2} s^{-1} sr^{-1})	IGM 10-200 LU (5 arcsec). CGM: 100-5000 LU (5 arcsec)	IGM: 5-100 LU (5 arcsec). CGM: 100-5000 LU (2 arcsec)	IGM 5-100 LU (5 arcsec). CGM: 100-5000 LU (1 arcsec)
R2a. Spectral Mapping (IFS): Contiguous survey regions	Field of view: ~4x4 arcmin^2	Field of view: ~2x2 arcmin^2	Field of view: ~2x2 arcmin^2
R2b. Spectral Mapping (MOS): Wide-field, multi-object mapping of galaxies and their CGM halos. Wide-field surveys of filamentary emission from cosmic web.	Field of view: (10-20) x (10-20) arcmin^2	Field of view: (2-5) x (2-5) arcmin^2	Field of view: (2-5) x (2-5) arcmin^2
R3. Cosmic volume (at low z)	IFS/MOS: 10^4 / 10^5 Mpc^2	IFS/MOS: 10^4 / 10^5 Mpc^2	a) IFS/MOS: 10^5 / 10^6 Mpc^2
R4. Spectral range	Observe Lyα, OVI1033, CIV1550 over $0.2 < z < 1$	Observe Lyα, OVI1033, CIV1550 over $0.2 < z < 1$	Observe Lyα, OVI1033, CIV1550 over $0.05 < z < 1.5$
R5. Velocity resolution	100-300 km/s	50-100 km/s	50-100 km/s
R6. Spatial resolution sufficient to resolve CGM components from central galaxy (~5-20 kpc)	20-40 kpc (~5 arcsec)	10-20 kpc (~3 arcsec)	3-7 kpc (~1 arcsec)

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