IGM and CGM Emission Mapping: A New Window on Galaxy and Structure Formation

Thematic Areas: Galaxy Evolution, (Cosmology and Fundamental Physics)

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The Promise of IGM/CGM Mapping

The IGM traces the cosmic web of matter in the Universe, forms and connects galaxies, fuels them throughout time, and may be profoundly changed by their feedback of energy, matter, and chemical elements. The Circum-Galactic Medium (CGM) traces the flow of matter, energy, and enriched elements between galaxies and the IGM. These flows may determine when and why a galaxy starts and stops star formation, its enrichment history, and the origin and evolution of its angular momentum and morphological type.

The IGM and CGM are the dominant phase of the baryons in the Universe, trace structure growth from linear to non-linear scales, and may drive the star formation history of the Universe. Explaining the evolution of galaxies requires understanding the co-evolution of their CGM halos. Because it is faint, low surface brightness, and challenging to interpret, we are just beginning to map emission from the IGM and CGM.

Progress in the next decade will be made by attacking these questions:

1) How does Lyα emission trace baryons? Lyα is the strongest tracer of IGM/CGM emission, and has been detected in gas clouds at high redshift. But radiative transfer effects make the interpretation of Lyα emission problematic.

2) What is the structure of galaxy halos? Galaxy halos consist of dark and baryonic matter. The distribution, temperature, density, and kinematics of the baryonic halos may be intimately entwined with the galaxies in those halos, their star formation histories, and the properties of the dark matter halo.

3) How does gas get into galaxies? There is theoretical and early observational indication for cold accretion inflows fueling on-going galaxy growth. The if, when, and how of these inflows can be determined with large surveys that connect inflows with galaxy properties.

4) How does gas leave galaxies? Outflows can eject gas, energy, and metals from star-forming galaxies (and galaxies with accreting massive black holes), sometimes shutting down (quenching) star formation.

5) What is the intensity of emission from the filamentary IGM, the cosmic web? Because it is brighter, progress analyzing the structure and physics of CGM halos and their co-evolution with galaxies should be great. The detection of the general cosmic web is more challenging, but early measurements will support the conception of more ambitious future missions to map it.

These questions can be answered in the next decade using ground integral field spectrometers designed for the lowest surface brightness emission on ~4-30 m class telescopes. (300-1100 nm, z_{Lya}~2-8) and space-borne emission line spectrometers on suborbital platforms, long duration balloons and sounding rockets, and explorer-class missions (125-300 nm, z_{Lya}~0-2). They will provide the design and scientific framework for future large, dedicated experiments.

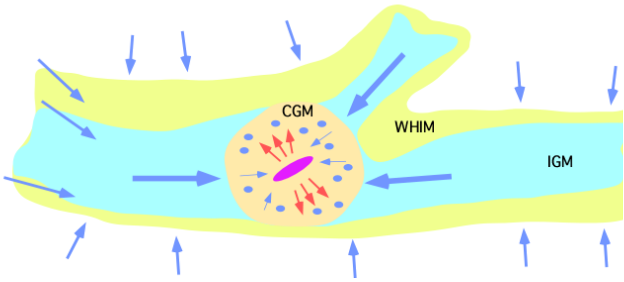
Motivation for IGM/CGM Mapping

We have reached the age of precision cosmology, and we have determined the initial conditions for structure formation. Yet, we lack a predictive theory of baryonic structure formation.

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. Dark matter halos, characterized by the overdensity parameter $\delta \equiv \rho / \bar{\rho}$, collapse and virialize with $\delta \sim 200$. 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. 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, and the resulting cooling radiation has never been detected.

Massive stars formed within the evolving galaxies create energetic stellar winds and supernova explosions, which inject energy and heavy elements 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% of the baryons. Our view of the dominant IGM/CGM component is based largely on the powerful but restricted information from QSO absorption line studies.



Prop-erty	Component			
	Cosmic Web	**Web/ Halos**	**Dark Halos**	**Gal-axies**
Baryon & structure tracer	IGM *fuel*	WHIM *baryons metals*	CGM *infall winds metals*	*disk galax-ies, 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 ab-sorption	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	
Detecta-ble by	10-30 m IFS	10-30 m IFS	Low z: ~1 m IFS; high z: 10-30 m IFS	

Figure 1. *Components of the IGM, none of which has ever been mapped in emission.*

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, but remains to be confirmed with emission maps.

IGM and WHIM: Most of the web is moderate overdensity ($1<\delta<100$) gas ionized by the metagalactic UV background from QSOs and possibly galaxies, 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 ongoing enrichment by galactic winds. As time goes on, the relentless pull of dark matter causes larger and larger structures to decelerate their expansion and then collapse into hotter, more massive but more tenuous filaments and clusters. At z=2, the observed Lyα forest and galaxies can account for all the baryons. But at z=0 we suspect most baryons have collapsed into a Warm-Hot Intergalactic Medium, $T_{vir}\sim10^5$-10^7K,) which produces weak, broad, difficult to detect Lyα absorption, and may produce most of the z~0 OVI absorption.

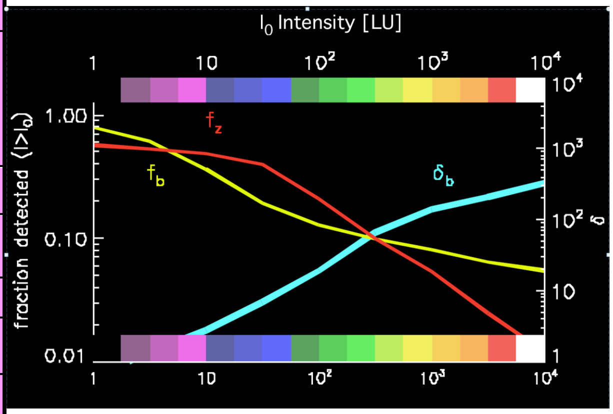


Figure 2. *Estimated IGM Lyα emission line intensity [1 LU = 1 ph $cm^{-2}s^{-1}sr^{-1}$]. vs. baryon overdensity δ_b (cyan curve) at z~0.5. Fraction of baryons detected Lyα intensity above I_0 (f_b: yellow curve), and fraction of metals detected for OVI1033 line measured with intensity above I_0 (f_z: red curve).*

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}).

Need for IGM Mapping There has been a long and productive effort to probe the IGM using QSO absorption lines and X-rays 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 bright (and therefore obscuring) and sparsely distributed QSOs. Future extremely large telescopes will enable tomographic absorption line mapping using background galaxies, and coupling these with emission maps will yield a completely new and synoptic picture.

Emission from the IGM and CGM, while tenuous, can and will be detected by new ground and space-based spectrometers. In Figure 2 we show how the intensity of Lyα scales with overdensity δ, a good redshift independent predictor of intensity. Table 1 shows typical emission strengths and feature sizes vs. Lyα redshift and observed wavelength, in comparison to the sky background and sensitivities of planned instruments. Processes that contribute to emission include radiative recombination, collisional excitation, and photon pumping. Dust absorption will be negligible in these metal poor, low density regimes. We also expect to detect OVI1033, CIV1549, and other strong metal line species in CGM and WHIM. The physics of the predictions, particularly for the IGM, is straightforward but awaits observational tests.

Science Questions

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 long and tortuous, IGM emission mapping will provide a completely new perspective that could lead to fundamental breakthroughs, by addressing these questions:

Question 1: How does Lyα and other strong UV emission lines trace IGM/CGM?

Lyα emission is the strongest and potentially most powerful tracer of the IGM/CGM. The challenge is that when Lyα is bright it is usually optically thick, and scattering in the strong resonance line complicates the extraction of physical parameters from Lyα maps [1, 2].

The key is to develop a calibration set of objects for which critical physical parameters can be independently assessed and compared with Lyα properties. The primary calibration set should be obtained at low redshift in order to maximize the corollary data available. Ideally the corollary data set for each object should include HI gas maps (e.g., 21 cm), HI absorption data (QSO or galaxy background objects), ionized gas tracers (Hα, etc.), and detailed maps that locate sources of Lyc and Lyα input (e.g., HST). This should be coupled with Lyα 2D (ideally, spectroscopic) mapping, e.g., integral field spectroscopy (IFS).

The calibration data set should be large enough to be distributed over a range of galaxy types, star formation rates and surface densities, stellar and halo masses, environments, and morphological types, and location and distribution of primary emitting objects. Some will be illuminated internally by star forming galaxies, and some externally by nearby QSOs. The set should be designed to include many objects that are representative analogs of high redshift objects. A high redshift calibration set should also be developed, albeit with a more limited set of corollary tracers and sensitivity.

Other strong UV resonance lines (HeII, CIII/CIV, etc.) are critical for supplementing the Lyα observations, constraining temperature, ionization, metallicity, and Lyα radiative transfer effects, and will round out the calibration set.

A key element of this investigation will be tying the multivalent observations to numerical simulations. We envision a massive effort to produce a "grid" of high resolution simulations of galaxies and their CGM halos. The grid would explore to date unconstrained parameter space of physical parameters, notably those related to gas, energy, and metal-bearing feedback, subgrid physics, multiphase gas evolution including turbulent mixing, evaporation and condensation, cosmic ray coupling, and magnetic fields. Forward modelling of these simulations into observable datasets (such as IFS data cubes) at multiple epochs will create a large training set of simulations with known input physics. Machine learning based on the training sets can be used to extract physical parameters from the calibration and other observation survey sets.

Bridge modelling must be developed as part of this effort that can span the gap between a finite number of particular realizations and the particular circumstances extant in observed systems.

Question 2: What is the structure of galaxy halos, and does this structure relate to the galaxy properties?

It is now known from observations and predicted by theory that CGM halos contain significant baryonic content that extend to the virial radius, are multiphase, and are metal enriched. But to date we are limited to a statistical picture of halo structure built up by combining many separate systems with single (or at most double) line of sight probes using background QSOs. Lyα emission maps of Lyα halos using IFS has now demonstrated the presence of extended halo gas in high redshift galaxies [3-5].

The first application of the results of Question 1 will be to determine the structure of CGM halos in a large number of objects at low and high redshift. The following physical parameters are potentially extractable and of great interest: 1) Density, temperature, and metallicity distribution of $10^{4\text{-}6}$K gas; 2) kinematic structure of halo gas; 3) mass, momentum, energy, and angular momentum of halo gas; 4) dark matter distribution traceable by halo gas kinematics.

A large set of halos with galaxies filling parameter space in the stellar mass, halo mass, star formation rate, and morphological planes should be surveyed in order to search for co-evolutionary trends that may probe causation. For example, does cold accretion drive star formation episodes? Is star formation quenched by feedback in low and high mass halos? Is morphological evolution driven by galaxy-halo gas flows?

Question 3: How does gas get into galaxies?

Galaxies form when the baryonic gas in dark matter halos can cool and collapse by orders of magnitude in density. Galaxies continue to form stars over time as more gas accretes from the CGM reservoirs, which may in turn be replenished by inflow from the IGM. Gas may cool and accrete in two very different ways, which could help explain why galaxies show a stark dichotomy in properties in the local Universe (blue, star-forming and red, passively ageing) [6, 7]. Hot accretion may occur in higher mass halos, with gas gravitationally cooling (precipitating) from 10^6K, roughly spherically (classic “cooling flow”). Cold accretion, expected to dominate in lower mass halos, at higher redshift, and in lower density regions at $z\sim0$, proceeds through the lower temperature ($10^{4.5}$K) ionized phase with gas flowing directly from filaments of the cosmic web.

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 CGM mapping is to determine whether the cessation of the delivery of fresh fuel explains the catastrophic fall in cosmic SFR in recent times.

In the last decade there has been tentative evidence supporting the cold accretion picture, both from absorption line and emission line observations. In the latter case, filamentary emission [8, 9] and candidate “cold-flow in-spiral” systems have been discovered and mapped using IFS [10, 11]. Evidence for cold flows and significant accretion of angular momentum is supported by theory and simulations [6, 12-18]. Ideally observations of “cold gas” would be combined with hot gas halo probes (e.g., x-ray absorption and emission), in order to sort out a mass sequence, and probe the regime (quite likely a large percentage of halos) in which both cold and hot accretion are active.

Question 4: How does gas leave galaxies?

One of the central missing elements in galaxy evolution models is an accurate physical understanding of the effects of galaxy 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 (possibly delaying accretion and star formation), and enriching the CGM. Feedback is constantly invoked to solve outstanding problems in galaxy formation theory, including the mass/luminosity function at high and low masses, the discrepancy between predicted and observed angular momenta in disks, and the M_{BH}-σ relation.

Galactic scale winds have been detected at low-moderate redshift using optical and near UV emission lines and at high redshift using rest-UV spectroscopy and interpretation of Lyα and other UV resonance line profiles.

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. Simultaneous mapping in Lyα, OVI, and CIV (and other lines), can distinguish between radiative cooling, accreting gas from shocked and outflowing gas using kinematic maps, line ratio diagnostics, and by making controlled comparisons between the halos of similar masses with very different SFR in their central galaxies.

A fundamental outcome of feedback is to inject metals into the IGM. This process is crucial to the chemical history of stars, galaxies and the IGM. By mapping the relative distribution of CIV, OVI, Lyα, and other lines around star-forming or post-starburst galaxies we can constrain the metallicity of the gas and map this vs. distance from the sources.

Question 5: What is the intensity of emission from the filamentary IGM, the cosmic web?

The ultimate potential of IGM/CGM mapping can only be settled by detecting the emission, establishing its origin in the IGM and CGM and determining the typical emission strengths in various regimes. Instruments are being conceived and built which should achieve unprecedented diffuse sensitivity. Observations sensitive to intensities ~1000LU (1 LU [line unit] = 1 ph $cm^{-2}s^{-1}sr^{-1}$) on scales of ~10 arcsec will detect CGM emission from galaxy halos.

These instruments, or future upgrades, may also detect the fainter but more extended emission from filaments of the cosmic web powered the metagalactic ionizing background, either by direct imaging or by statistical means. Large, sensitive, narrow-band or spectroscopic surveys will find regions where the average background is boosted by presence of a nearby QSO, making this web emission more detectable.

IGM emission mapping is potentially a new cosmological tool, and once the typical emission levels and excitation physics are established it will be possible to design instruments and missions that can map the cosmic web.

Means

To answer these compelling questions, IGM emission mapping requires imaging spectrographs covering the rest UV (simultaneous observations of redshifted Lyα, OVI1033, and CIV1550 as well as other strong UV emission lines), excellent diffuse sensitivity 10-1000LU in regions of a few to 10 arcsec, excellent rejection of foreground emissions, sufficient spectral resolution to map kinematic flows and line profiles, sufficient spatial resolution to isolate point sources from IGM gas, and the capability to perform surveys of large enough cosmic volumes to make statistically robust physical connections between observables.

At high redshift (z~2-6), moderate to large telescopes (4-30 m) equipped with optical 2D imaging spectrographs designed to detect and map IGM emission can exploit modest new investments in instruments to initiate a completely new field of observational study. Surveying significant cosmic volume and exploiting cosmological applications may require major new instruments and even dedicated telescopes. Dedicated experiment designs are required to combine ultra-low surface brightness sensitivity, exquisite sky subtraction, and high spectral resolution, but the technologies exist.

At lower redshift (0<z<2) the strong UV lines must be mapped using new space instruments. In particular, the local Universe is populated with objects with extensive multiwavelength coverage and bright UV emission that can be detected and mapped with a moderate size space mission. The low UV sky backgrounds make detections less challenging and possible with modest apertures. Initial detections may be performed from suborbital platforms such as conventional or long-duration balloons (~200 nm, Lyα z~0.7), or possibly sounding rockets (125-300 nm, 0<z<1.5). Mapping and surveying will require an explorer-class mission, which will provide the Lya calibration set, first detections and characterization of IGM, WHIM and CGM emission at low redshift, and the essential design context for a large-aperture UVOIR spectroscopic mission that will exploit the full potential and diagnostic power of IGM emission.

New UV detector technology will provide good efficiencies and detection of low redshift IGM emission for ~1 meter class space-borne telescopes foreseeable in the next decade.

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