THE SCIENCE ENABLED BY UV EMISSION LINE MAPPING OF THE INTERGALACTIC MEDIUM AND THE CIRCUM-GALACTIC MEDIUM

A Science White Paper submitted to the Astro2010 Survey

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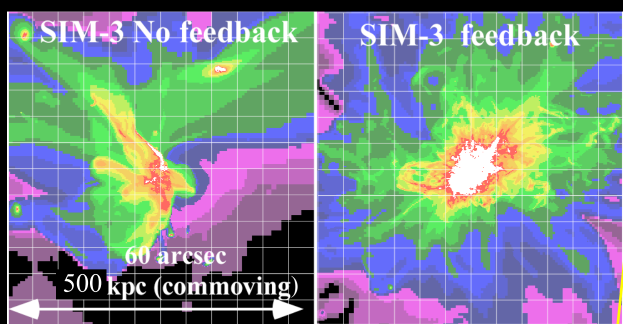
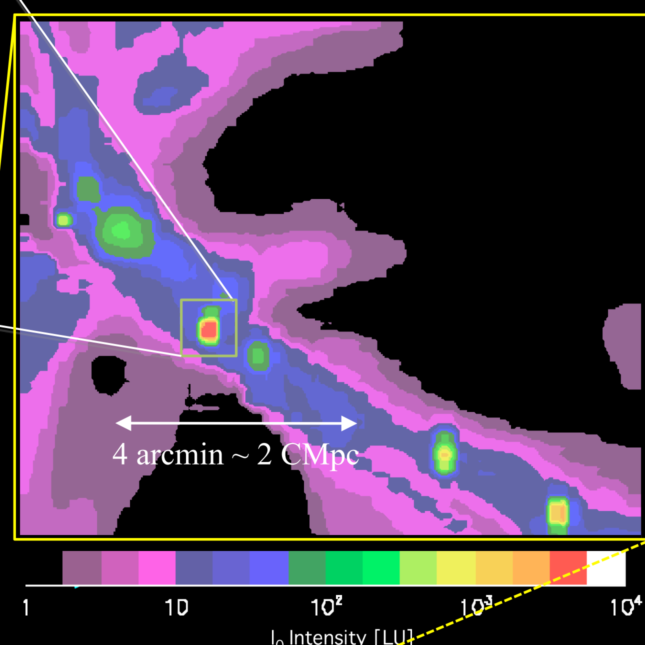
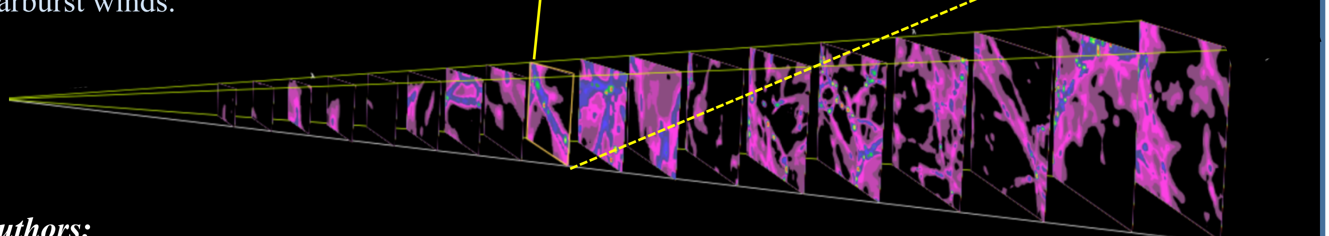




Cover Figure: Bottom: IGM Lyα cone 0.05<z<1.2 Upper right: a filament of the cosmic web showing typical emission levels (~30-100LU [ph cm^{-2} s^{-1} sr^{-1}] in bright regions and ~3-30LU in faint outskirts.) at z=0.4. Upper left simulation of Circum-Galactic Medium (CGM) around a star forming galaxy without [left] and with [right] starburst winds.



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The Promise of IGM Mapping

In the coming decade, we will discover and map emission from the Intergalactic Medium (IGM). 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. IGM emission can reveal one of the last, undiscovered forms of luminous matter in the Universe that may constitute the majority of baryons. IGM emission will be used to trace the flow of gas into and out of galaxies, "closing the loop" on galaxy evolution models. IGM emission will provide a new tool for mapping large scale structure and for cosmology.

These questions are ripe for attack before 2020:

1) How strong is IGM emission? What is its relationship with absorption, and can emission mapping offer a new and powerful cosmological tool?

2) Where are the baryons at z~0? What fraction of the z~0 IGM is in a diffuse 10^5-$10^{6.6}$ phase?

3) What is the total baryon content (the Circum-Galactic Medium, or CGM) of the dark matter halos hosting galaxies? How does this gas content vary with redshift, galaxy type, evolutionary stage, and halo mass and environment?

4) Is CGM gas inflowing to fuel new star-formation or outflowing due to feedback? Can we determine how the gas measured in the CGM is inflowing to the galaxies, outflowing due to winds or AGN energy inputs, replenished by inflow from the IGM, and whether these gas flows regulate star formation history?

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. (300-1000 nm, z_{Lya}~2-7) 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 framework for future large, dedicated experiments.

Motivation for IGM Mapping

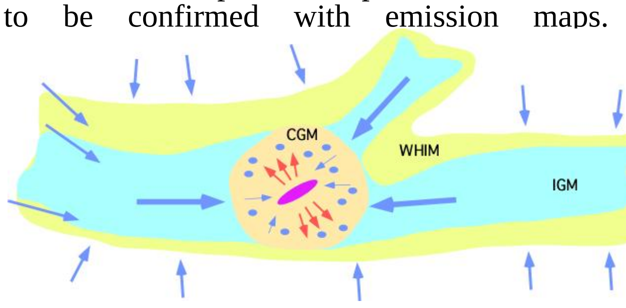
Recent, spectacular measurements of the cosmic microwave background by NASA Balloons and Explorers [1, 2] have opened the age of precision cosmology. We understand the initial conditions and constituents that seeded the cosmic structures we see today. At the same time ***we lack a predictive theory of 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 δ~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. 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, but remains to be confirmed with emission maps.



	Component			
Property	**Cosmic Web**	**Web/ Halos**	**Dark Halos**	**Galaxies**
Baryon & structure tracer	IGM *fuel*	WHIM *baryons metals*	CGM *infall winds metals*	*disk galaxies, 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. *Components of the IGM, none of which has ever been mapped in emission.*

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 on-going 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.

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}).

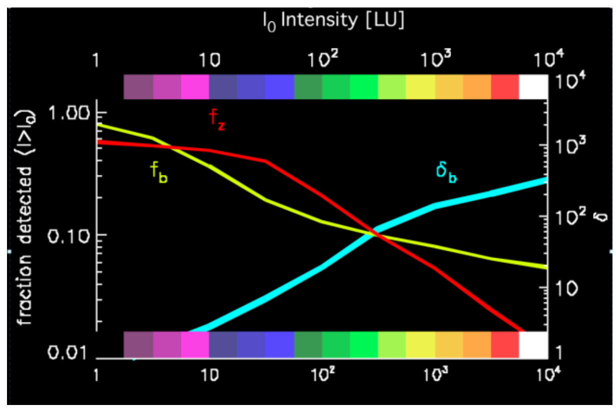


Figure 2. *Estimated IGM Lyα emission line intensity [1 LU = 1 ph $cm^{-2}s^{-1}sr^{-1}$]. vs. baryon overdensity δ_b (cyan curve) at z~0.5. Fraction of baryons detected Lyα intensity above I_0 (f_b: yellow curve), and fraction of metals detected for OVI1033 line measured with intensity above I_0 (f_z: red curve). Intensity color scale is same as shown in Cover Figure and Figure 3.*

Need for IGM Mapping There has been a long and productive effort to probe the IGM using QSO absorption lines. The high density IGM in rare galaxy clusters has been mapped in X-ray emission for decades. 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. While future giant telescopes will enable tomographic absorption line mapping using background galaxies, emission maps will yield a completely new and synoptic picture.

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 new ground and space-based spectrometers. The cover figure shows typical emission structures tracing the cosmic web and CGM. In Figure 2 we show how the intensity of Lyα scales with overdensity δ, a good redshift independent predictor of intensity. Figure 3 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.

IGM Emission mapping provides fundamentally new information that will complement QSO absorption line and galaxy evolution studies:

- Detection of low filling factor or warm-hot gas missed by absorption lines
- 3D maps of gas and metals; spatial relationship of IGM, galaxies, QSOs
- IGM cloud sizes, structure, density, mass,
- Kinematic mapping and gradients that probe flows, rotation, mechanical, radiation inputs
- Probe of cooling, energetics, ionization, recombination, and multi-phase structure

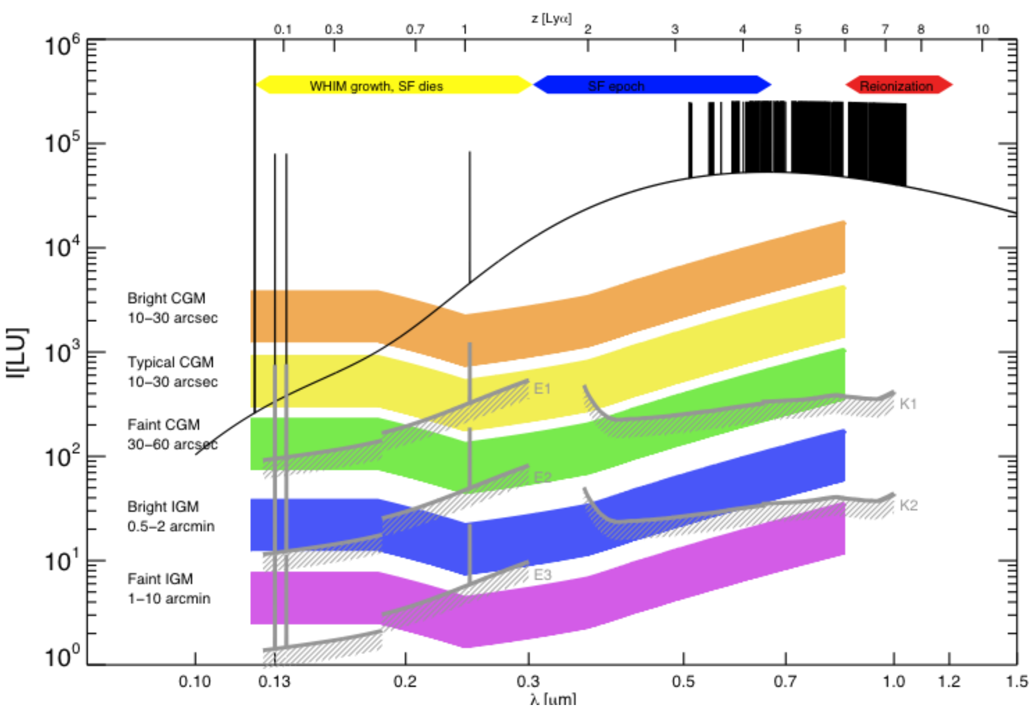


Figure 3. *Top: typical emission line strengths for Lyα from the CGM and the IGM. Bands show IGM emission levels, red: bright CGM, yellow: typical CGM, green: faint CGM, bright filaments, pink: faint filaments. Black curve shows typical sky background. Grey hatches show typical sensitivities for a range of feature size and exposure for UV explorers (E: 1 Msec, E1-10" features, E2-60", E3-240") and 10-m class instruments (K, K1-8 hours, 10" features, K2-80 hours, 60" features). Deepest sensitivities (E3, K2) can be reached directly with deep exposures and extended emission (filaments) or by statistical means (stacking, cross-correlation, etc.)*

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 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. Instruments are being conceived and built which should achieve *unprecedented diffuse sensitivity*. As we show in Figure 3, observations sensitive to intensities ~1000LU (1 LU [line unit] = 1 ph $cm^{-2}s^{-1}sr^{-1}$) on scales of ~10 arcsec should detect CGM emission associated with gas in galaxy dark matter halos. These instruments may also detect the fainter but more extended emission from filaments of the cosmic web, either by direct imaging or by statistical means.

Modern simulations are converging on the input physics and the predicted emission strengths in the diffuse IGM. While the physics of the CGM is more complex, the higher densities and input of energy from nearby galaxies imply that they are much brighter than the diffuse IGM**.**

A key to establishing the basic physics of the emission and validating models will be the comparison of emission and absorption line strengths obtained in different density and temperature regimes in QSO fields and using tomographic mapping of absorption with galaxies on 30 meter class telescopes.

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. We describe three potential cosmological applications here.

Map large scale structure (LSS) using IGM Emission. Large galaxy surveys are the current tool of choice to map LSS. But fundamental difficulties remain: the standard models predict large numbers of unseen dwarf galaxies surrounding large galaxies [4]; galaxies are a biased tracer of structure; and measured power spectra have disagreed with predictions on large scales. Simulations show that the diffuse IGM is an excellent tracer of LSS [5-7], and QSO absorption line statistics coupled with CMB measurements break many degeneracies [7, 8]. IGM emission could offer a breakthrough improvement in cosmic variance and 3D mapping of LSS at low density and bias. Statistically robust IGM correlation functions can be constructed yielding a powerful constraint on structure models.

Map the metagalactic UV ionizing background using Lyα fluorescence. The metagalactic ionizing background determines the ionization and energetics of the diffuse IGM and the diffuse ISM in low mass galaxies. It is central to the physical interpretation of QSO absorption lines and determining the baryon density. Yet its strength over cosmic time and the contribution from galaxies remain very uncertain. The Lyα emission floor provides a constraint, perhaps even a measurement of this background. The highest column density IGM regions "reflect" 65% of the metagalactic ionizing background back as Lyα emission [9]. New instruments will measure the bright end of the luminosity function, and map it with respect to QSOs to measure the mean field. Local sources of star formation will be mapped and removed using imaging spectroscopy. This will constrain the background and probe its spatial uniformity.

Map "Einstein's Ruler" using the Alcock-Paczynski Test. The idea [10] is simple: use a standard ruler and compare the distance along the line of sight, measured by velocity width from cosmic expansion, to distance in the plane of the sky. In this way you can measure the Hubble velocity and its acceleration away from Einstein-de Sitter due to dark energy. IGM mapping offers the possibility of using IGM scales as the ruler, by cross-correlating IGM emission with QSO absorption, and IGM emission with itself. The ratio of the line-of-sight width to the transverse width is the AP test.

Question 2: Where are the baryons at z~0? What fraction of the z~0 IGM is in a diffuse 10^5-$10^{6.5}$ phase?

Map the Hidden Baryons. The web of baryons is the dominant reservoir of normal matter. The web fuels galaxy formation and evolution, and traces the large scale structure of the Universe. It is crucial to map the distribution of this major, unseen component of the Universe. Absorption line measurements cannot *map* and may miss warm, broad-line WHIM components as well as gas locked in low filling factor substructure. Challenging X-ray measurements can probe 10^6-10^7K gas, but UV lines sensitively probe what may be the majority phase at 10^5-$10^{6.5}$K.

New instruments can map a substantial fraction of the missing baryons. As we show in Figures 2 and 3, 10-20% should be detected by direct mapping in small UV orbital missions, and as much as 40-60% by power spectrum detection.

Weigh the Hidden Baryons. While mapping a completely new luminous component of the Universe is worthy, we seek to convert these maps into a census of mass, a true challenge. The good news is that models predict that the majority of baryons are in the diffuse WHIM component in which the physics and emission processes are simple. Models make definite predictions for multivariate distributions of luminosity, size, and spatial relationship with galaxies in the WHIM and IGM. For example, the pixel luminosity function (PLF) (number of pixels vs. intensity) is a direct tracer of the total mass. Both direct and statistical methods can be employed. QSO absorption observations will furnish a detailed cross-calibration of emission strength vs. absorption system properties to validate our models and emission diagnostics.

Question 3: What is the total baryon content of the dark matter halos hosting galaxies in a 10^4-10^6K phase? 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 [11, 12]. But we have no true maps.

Bright Lyα blobs and radio galaxy extended emission are now well studied examples of the brightest gas probably excited by powerful AGN or starbursts. There is tantalizing evidence for emission from more typical CGM gas from Lyman Break Galaxies at z~2 [13] and z~0 [17], at levels of 3,000-30,000LU.

New instruments will detect and map emission from CGM using Lyα and other ionization, temperature and abundance diagnostics such as OVI1033, CIV1549, CIII977 and HeII1640. Calibrated with absorption line information from HST/COS and 10-30 m ground telescopes, we will map the extent of CGM gas and its spatial relationship to galaxies, correlate CGM emission and galaxy properties, including key parameters measured in the rest UV by the IGM imaging spectroscopy itself such as star formation rate, galactic wind features, and Lyman continuum radiation escaping the galaxy and ionizing the CGM.

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) [14, 15]. Hot accretion may occur in higher mass halos, with gas gravitationally cooling 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~0, proceeds through the lower temperature ($10^{4.5}$K) ionized phase with gas flowing directly from filaments of the cosmic web.

But there are almost no observational constraints on CGM gas reservoirs and accretion. Gas reservoirs could be detected and weighed by their emission. Gas cooling and releasing gravitational energy produces a characteristic line spectrum with OVI1033 dominating in $10^{5.5K}$ (hot mode) and CIV1549/CIII977 in $10^{4.5}$K gas (cold mode) in regions that have already been polluted with metals, and HeII1640 in primordially cooling halos, in addition to the ubiquitous Lyα. A major objective is to map and weigh the CGM, out as far as possible in the web, and use these maps to test models for ongoing gas cooling and accretion that fuels galaxies.

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 mapping is to determine whether the cessation of the delivery of fresh fuel, as traced by CGM/IGM emission, explains the catastrophic fall in cosmic SFR in recent times.

Question 4. Is CGM gas inflowing to fuel new star-formation or outflowing due to feedback? How much CGM gas is inflowing to the galaxies, outflowing due to winds or AGN energy inputs, replenished by inflow from the IGM? Do these gas flows regulate SF history, or are they regulated by star formation?

Map inflows fueling new star formation. While CGM physics is more complex than IGM, the emission is brighter. Modern simulations have the mass and spatial resolution to trace the flow of mass and energy on scales that are extremely useful, but the models are in desperate need of observational input. We can use a "forward modeling" approach to compare the observed distributions of the various lines to CGM models with different assumptions. More classical, line diagnostic approaches, adapted to IGM conditions, are also possible. The outline is simple: we constrain the *excitation* mechanism (cooling, shock, scattering, or photo-ionization) using kinematics, line ratios, and the central galaxy properties. We use line ratios to determine *temperature* and *metallicity*, we use these three with intensity to derive *density*, and use size to determine *mass*. Density, temperature, and metallicity also provide us with *cooling time* which combined with mass leads to the cooling or accretion rate. Upcoming experiments can detect mass fluxes as low as $\sim 1 M_{\odot}\ yr^{-1}$, a level that can strongly impact the evolutionary path of galaxies.

Map matter and energy outflows from galaxies into the CGM. 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 central black hole-bulge mass correlation.

Galactic winds at $z\sim3$ 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 hundreds of kiloparsecs into the surrounding medium. The indirect evidence is that metal line systems are correlated with star forming galaxies over vast scales and have velocity widths of hundreds of km/s. These effects must continue through the end of the star formation epoch at $z\sim1$, since the number density of UV luminous galaxies remains high until $z<1$ [16].

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. Outflowing gas at velocities that produce x-ray temperatures will strike inflowing cool gas fueling on-going star formation and light it up in UV with radiative shocks. Feedback produces profound differences in the CGM emission morphology and kinematics (see cover figure, top left). Simultaneous mapping in Lα, 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, and also determines the ionization and cooling of IGM/CGM gas. At high z IGM absorption lines probe feedback, galaxy and chemical evolution that is imprinted today in stellar populations and luminosity functions. By mapping the relative distribution of CIV, OVI, Lyα, and other lines around star-forming or post-starburst galaxies we suspect have injected metals into the IGM, we can constrain the metallicity of the gas and map this vs. distance from the sources.

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 20-200LU in regions of a few to 10 arcsec, excellent rejection of foreground emissions, sufficient spectral resolution to map kinematic flows, 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. An example is the Keck Cosmic Web Imager, a path-finding instrument planned for first light in 2012 (Sensitivity is shown in Figure 3, K1-K2). 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 for these instruments exist.

At lower redshift (0<z<2) the strong UV lines must be mapped using new space instruments. 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 orbital sounding rockets (125-300 nm, 0<z<1.5). Mapping and surveying will require an explorer-class mission, which will provide the first detections and characterization of IGM, WHIM and CGM emission at low redshift (see Figure 3, E1-E3). Such a mission will provide the essential design context for a moderate-to-large-aperture (4-8 meter) UV spectroscopic mission that will exploit the full potential and diagnostic power of IGM emission.

Critically, new UV detector technology must be brought to fruition to provide good system efficiencies and guarantee the detection of low redshift IGM emission for ~1 meter class space-borne telescopes foreseeable in the next decade.

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