# Astro2010 Science White Paper:

The Cosmic Web



Panel: *The Galactic Neighborhood* Panel: *Galaxies Across Time* 

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#### Introduction to the Cosmic Web

Except for the small percentage of baryons attributable to galaxies and the intracluster medium, all of the baryonic mass in the universe is contained in the intergalactic medium (IGM). The IGM traces the large scale structure of cold dark matter and comprises the raw material out of which galaxies, stars, planets, and all life as we know it are eventually formed. The IGM, which was smoothly distributed in the early universe, organized into a cosmic web of large-scale structures with the passage of time. As the morphology of the cosmic web evolved, so did its physical conditions. Energy released by the gravitational collapse of filamentary structures heated the gas to high temperatures ( $10^5 - 10^7$  K). The Ly $\alpha$  forest, which dominated the baryon budget at high redshift, thinned rapidly, and the warm-hot component of the IGM became more important. The warm-hot IGM now accounts for roughly 30-50% of the IGM at redshift zero, with a slightly smaller amount (perhaps 30-40%) remaining in the remnants of the photoionized Ly $\alpha$  forest (Cen & Ostriker 1999; Davé et al. 2001). As a result of this evolution, we know considerably less about the IGM in the present-day universe than we do at high redshift. Despite progress in ultraviolet instrumentation over the past three decades, there exists only a handful of spectra of the z < 1 IGM of the quality obtained for hundreds of sight lines at  $z \sim 2$ .

The growth of large-scale structures in the cosmic web and the assembly of galaxies continue to the present day. The exchange of mass and energy between the IGM and galaxies is a twoway conduit. Galaxies accrete intergalactic matter. Shocks and galactic winds driven by

supernovae modify the structure of gas in the surrounding IGM. These outflows inhibit the infall of material onto galaxies, thereby regulating the formation of new stars (Birrnboim & Dekel 2003; Keres et al. 2005). Cosmological structure simulations that incorporate galactic superwinds predict that metal-enriched regions of size ~0.1-1 Mpc filled with  $10^5$ - $10^6$  K gas should surround starburst galaxies (Cen et al. 2005). Observations of the feedback and hot gas production



Figure 1: Gas temperature distribution for cosmological models with and without supernova feedback (see Cen & Ostriker 2006).

mechanisms are needed to specify the treatment of galaxy formation and supernova feedback in these simulations in a self-consistent manner. This is one of many critical inputs for hierarchical structure models that form the basis for our view of how the universe evolves, but which have yet to undergo substantial observational validation.

A primary challenge in the next decade is to advance beyond this general framework and determine how the cosmic web is organized, how it has changed with time, and how it is related to galaxies. It is time to rethink what we already know about the cosmic web and recast general questions such as "Where are the Baryons?" (Answer: In the intergalactic medium) into more scientifically directed questions that will deepen our understanding of how galaxies and the universe evolve.

How is intergalactic matter assembled into galaxies? To what degree does galaxy feedback regulate and enrich the IGM? Where and when do these processes occur as a function of cosmic time? These are not easy questions to address, but they can be answered in the next 10-20 years if a concerted effort is made to explore the low-redshift IGM as intensively as we've already explored the high-redshift IGM. The answers will place our understanding of how galaxies are assembled on par with other areas of galactic studies (e.g., stellar populations, galactic dynamics, star-formation), and will provide rigorous tests of cosmological simulations used to describe the evolution and fate of the universe.

# **Observations of the Present-Day Cosmic Web**

Observationally, most of the information about the low-redshift intergalactic medium comes from absorption-line spectroscopy of QSOs with HST, FUSE, and (to a lesser extent) Chandra and XMM. Primary tracers of the Ly $\alpha$  forest include the H I Lyman series and metallines of varying ionization, which are also important diagnostics of the metallicity of the gas. Higher ionization lines of O and Ne track the warm-hot IGM. UV species are both the easiest to detect and the most informative because of the wide range of accessible ionization stages.

Table 1: Components of the IGM							
		T (K)	Primary Metal-Line Tracers	Waveband			
Cool Photoionized Lya forest		$< 3x10^4$	C II, C III, Si II, Si III	UV			
Warm Photoionized Lya forest		$3x10^4 - 10^5$	C III, CIV, O III, O IV, O VI	UV			
Warm-Hot IGM (WHIM)	Warm	10 <sup>5</sup> - 10 <sup>6</sup>	O VI, O VII, Ne VIII	UV, X-ray			
	Hot	$10^{6} - 10^{7}$	O VII, O VIII	X-ray			

Due to the 'thinning' of the Ly $\alpha$  forest at z < 1, the statistical sample of UV absorption lines in the complete HST and FUSE archives is the equivalent of that from a handful of z > 2quasar spectra obtained from the ground with Keck or VLT. A more stunning scarcity of information exists for the warm-hot IGM; the total redshift path probed for O VI by the highest quality HST/STIS spectra is only  $\Sigma(\Delta z) \sim 3-4$ . This is exacerbated by the fact that there is no comparable counterpart at high redshift to observe from the ground! What we know about this poorly understood component of the cosmic web comes from a sample of less than a hundred low-z O VI absorbers (Tripp et al. 2008; Danforth et al. 2006; Thom & Chen 2008), two Ne VIII detections (Savage et al. 2005; Naraynan et al. 2009), and at best only a few O VII absorbers (Nicastro et al. 2005; Yao et. al 2008; Buote et al. 2009).

What do we know about the warm-hot gas? The observed O VI absorption systems have a variety of ionization and kinematical properties (see Figure 2). Some systems can be explained by simple photoionization models of the gas. Some are multi-phase and complex, having both high and low ionization components distributed in velocity. Others are clearly dominated by high ionization lines (no low ions and little H I) and probably trace collisionally ionized gas. The O VI absorbers typically have metallicities of 0.1-0.3 solar and appear to be located in a variety of environments ranging from galactic halos to groups of galaxies to voids.

Cosmological simulations predict that the amount and velocity distribution of the high ionization absorption depend strongly upon the past history of the collapsing sheets and filaments. Kang et al. (2005) suggest that O VI absorption should arise predominantly in warm collisionally ionized gas at T <  $10^5$  K (sheets), and O VII and O VIII should arise predominantly in hotter collisionally ionized gas at T ~  $10^6$ - $10^7$  K (filaments) – see Figure 3. Both components are expected to contribute significantly to the overall baryon budget of the IGM in their model.



Figure 2: HST/STIS spectra of Ly $\alpha$ , O VI, C II, and Si II at  $z \approx$ 0.2 toward two QSOs (Tripp et al. 2008). The left panel shows an example of a complex, multi-component, multi-phase absorption system. The right panel shows an example of a highly ionized O VI absorption system with little Ly $\alpha$  or lowionization absorption.

High spectral resolution ( $R \approx 45,000$ ) allows detailed line profile investigations that can be used to determine the ionization structure of the gas. Hubble data of this quality exists for less than 100 O VI absorbers.

Oppenheimer & Davé (2008) predict that many of the O VI absorbers, particularly weaker ones, should be located near galaxies and trace photoionized gas rather than collisionally ionized gas.

To distinguish between the possible origins for the absorbers and determine under what conditions they are appropriate will require 1) at least an order of magnitude increase in the number of absorption line observations of all components of the IGM listed in Table 1, and 2) spectral imaging of the IGM in key emission lines to reveal the relationship of the gas to galaxies. The installation of the Cosmic Origins Spectrograph (COS) in HST during Servicing Mission 4 will facilitate many additional absorption line detections of species ranging from Ly $\alpha$  to Ne VIII, but even this will yield just an initial cut at answering the questions posed above. It will take a more intensive approach with future observatories to address those questions fully.



Figure 3: The cosmic web at zero redshift (Kang et al. 2005).

#### Gas Accretion and the Evolution of Galaxies

Understanding how gas in the IGM gets into galaxies and how galaxies respond to inflow lies at the heart of understanding galactic evolution. There are several descriptions of how this accretion might work (see Birnboim & Dekel 2003; Keres et al. 2005). The mode of accretion depends on the depth of the potential well (galaxy type) and the location at which the intergalactic gas is shocked as it encounters that potential. Galaxies with  $M_{halo} > 10^{12} M_o$  accrete through the "hot mode", in which infalling gas is shocked near the halo virial radius to  $>10^6 K$ . In halos with  $M_{halo} < 10^{11} M_o$  a virial shock does not develop, and "cold mode" accretion can occur along narrow filaments extending far inside the virial radius. A third type of "multiphase"

accretion involves cooling of clouds within hot halos left over from earlier epochs of galaxy formation or previous mergers (Maller & Bullock 2004).

Working in the opposite sense of accretion are processes that remove gas from galaxies. For example, tidal interactions play significant roles in merger-intensive galaxy evolution (Elmegreen et al. 2007). Gas is removed from galaxies through tidal and ram pressure stripping, which can operate in galaxy groups (Kantharia et al. 2005) or during the accretion of gas-rich dwarfs onto giant galaxies (Mayer et al. 2007). Metal-enriched gas introduced into the IGM by these processes will be dynamically cool. The gas has relative and internal velocities characteristic of orbital speeds (Bournaud et al. 2004), unlike ejecta from galactic winds (see, e.g., Figure 4), which move material at galactic escape velocities (Adelberger et al. 2003; Heckman et al. 2001). The removal of gas from galaxies also results in the expulsion of metals back into the IGM.

Different prescriptions for galactic superwinds in cosmological simulations can lead to substantial differences in the predicted properties of the gas, as shown in Figure 1. As such, comparisons of the simulation results to observable quantities guide our understanding of how



Figure 4: Starburst galaxy M82. (X-ray: NASA / CXC / JHU / D. Strickland; Optical: NASA / ESA / STScI / AURA; IR: NASA / JPL-Caltech / Univ. of AZ /C. Engelbracht

# Where Do We Go From Here?

the IGM and galaxies transfer matter and energy back and forth (see Oppenhemier & Davé 2008). All of these accretion and gas removal theories have observational consequences that can be tested if the distribution of gas in the cosmic web around galaxies can be characterized through absorption and emission The observational challenge line spectroscopy. before us is to acquire datasets of sufficient sample size and with enough diagnostic power to address the various processes at work. The number of suitable background sources available for absorption line measurements is presently limited by the sensitivity of current instrumentation (HST/COS), and we still have no means for spectrally imaging the emission from key diagnostics of the gas (e.g., Lya, O VI).

In the near term, there is no doubt that a refurbished HST will make significant advances in our understanding of the IGM. The Cosmic Origins Spectrograph has a sensitivity 10-30 times greater than previous UV spectrographs aboard Hubble. Still, even with COS, it will be difficult to comprehensively address the issue of how the IGM and galaxies interact. Consider Figure 5, which shows an r-band image of the field around the bright QSO H1821+643. There are two prominent structures in the field, one at  $z \approx 0.245$  and another at  $z \approx 0.227$ . Toward the QSO, the IGM absorbers at these redshifts trace gas associated with the two groups of galaxies, but the extent of that gas, its relationship to the nearest galaxy (or galaxies), and its physical properties at locations other than directly toward the QSO are unknown because there are no other background continuum sources in the field observable with current instrumentation. We don't know whether the gas is integral to understanding the galaxy distribution or merely a byproduct of galactic effluence.

We suggest two complementary approaches to removing this observational roadblock. One involves dramatically increasing UV absorption-line sensitivity so that multiple sight lines can be probed through regions like that in Figure 5, and another involves making 3-D maps of the IGM Ly $\alpha$  and O VI emission. The first allows intensive investigations of gas near galaxies and sparse sampling of regions too diffuse ( $\delta = \rho/\overline{\rho} < 10$ ) to detect in emission (e.g., cosmic web filaments). The second reveals the distribution and extent of gas in galaxy halos, groups, and clusters at filament intersections ( $\delta \sim 10^2$ - $10^3$ ) where accretion and galactic winds operate.

Figure 5: A 5.5'x5.5' Gemini GMOS r-band image of the galaxies in the field around QSO H1821+643. The quasar is in the middle of the image (marked with a star). Photometricallyscreened galaxies with spectroscopic redshifts are circled when they are in the background of the quasar, and are identified with arrows (labeled with the redshift) when they are in the foreground at the redshifts of known absorbers along the QSO sight line. Two prominent groups at  $z \approx 0.245$  (green) and  $z \approx 0.227$ (blue) are present. The field is approximately 1.2x1.2 Mpc in size at a redshift of  $z \approx 0.25$ . In addition to allowing detailed line profile analyses and investigations of the gas ionization and metallicity, the excellent spectral resolution afforded at UV wavelengths facilitates accurate comparisons of the redshifts of the observed absorbers to the redshifts of galaxies.



# <u>Approach #1: Increasing ultraviolet absorption-line sensitivity</u>

Table 2 shows a comparison of exposure times for HST/COS and several larger versions of HST, up to 16m in size. The same exposure times apply to "optimized" telescopes having a factor of 4 improvement in system throughput over that available with today's (Hubble's) technology. This is a modest technical goal, and would be a very low cost alternative to doubling the size of the telescope primary. An optimized 2m telescope would be more efficient than Hubble. An optimized 4m telescope would have >10 times the sensitivity of Hubble and could reach down to  $m_{FUV} \sim 24$  in modest exposure times (~100 ksec). An optimized 8m telescope would be very powerful, probing ~100 times deeper than Hubble with short exposures.

Table 2: Gaining Depth with Aperture								
Flux (erg cm <sup>-2</sup> s <sup>-1</sup> Å <sup>-1</sup> )	GALEX FUV (mag)	Exposure Time to Reach S/N =10 at $R = 20,000$						
		HST / COS	4m HST	8m HST	16m HST			
			or	or	or			
			Optimized 2m	Optimized 4m	Optimized 8m			
$1 \times 10^{-15}$	19.2	9.8 ksec	3.6 ksec	900 sec	220 sec			
$1 \times 10^{-16}$	21.7	115 ksec	39 ksec	9.1 ksec	2.2 ksec			
$1 \times 10^{-17}$	24.2	2.9 Msec	700 ksec	110 ksec	24 ksec			
Calculations assume a 2-mirror OTA with 12% secondary linear obscuration, feeding a single reflection								
spectrograph with a detector dark count rate of $2.7 \times 10^{-4}$ cnt s <sup>-1</sup> per resolution element.								



Figure 6: Number density of QSOs as a function of GALEX FUV magnitude. Data from the SDSS DR5 and Stripe 82 surveys are shown. The DR5 data roll off at  $m_{FUV} \sim 21$  due to sample incompleteness at fainter magnitudes. The cumulative number density of QSOs brighter than a given magnitude are listed near the bottom of the plot. Although not shown, the galaxy density on the sky is increasing rapidly at magnitudes greater than  $m_{FUV} \sim 20$ , which will further increase the number of available background continuum sources for absorption line spectroscopy.

So how does increased throughput help? Figure 6 shows the number of QSOs per square degree per magnitude as derived from the Sloan Digital Sky Survey. At the bottom of the figure

are shown the cumulative numbers of QSOs per square degree at the indicated magnitude. A similar plot can be drawn for galaxies, which would greatly expand the number density of background continuum sources beyond  $m_{FUV} \sim 20$ . Even at a QSO number density of only a few per square degree, one can select sight lines next to hundreds of examples of any common galaxy, group, or cluster. In a statistical fashion, one could then produce a high-resolution map of the gas and metals surrounding such structures to compare directly against simulation predictions (e.g., Figure 6). With a large space telescope one could use multiple QSOs and distant galaxies as background continuum sources to dissect the gas distribution in fields known to have galaxies and gas at the same redshift (e.g., Figure 5). One could also systematically target individual nearby galactic coronae



Figure 6: A slice through the cosmic web (Cen & Ostriker 1999). Red regions are galaxies. Green contours trace metals. Blue contours trace  $10^5$ - $10^7$  K gas.

and groups of galaxies, for which it would be possible to observe the production sites of heavy elements (star-forming regions, SNe, emission nebulae), follow the processes by which the elements are transported within galaxies, and trace the expulsion of metals into the IGM.

### Approach #2: Imaging the Cosmic Web in Emission

Spectral imaging of the IGM through its emission is more challenging than absorption studies, but would provide detailed 3-D information about the structure and the properties of the gas that would be difficult, if not impossible, to obtain any other way. It is the best way to observe accretion and expulsion processes directly and unite the information available from galaxy redshift surveys and absorption line studies. Imaging Ly $\alpha$  and O VI emission could be done with a small (<1m) wide-field telescope in space at a location beyond the geocoronal emission of the Earth (e.g., at L2). Ly $\alpha$  maps are needed to trace the overall gas distribution of the cosmic web, and O VI maps would trace feedback processes in the metal-enriched regions of the warm-hot IGM near galaxies (e.g., Figure 1). Similar maps at X-ray wavelengths would provide information about hotter gas.

A portion of a cosmological simulation showing the O VI emission in the cosmic web is shown in Figure 7. The key to testing models such as these, whether it is through Ly $\alpha$  or O VI emission, is sufficient grasp (sensitivity x field of view) to detect emitting structures. Here too, modest investments in technologies that increase system throughput (e.g., detectors, optical coatings) will have a large impact on science return. Resolution is also important. The angular extent of filaments is expected to be a few arc minutes at  $z \sim$ 0.2, and the velocity widths are ~100 - 300 km s<sup>-1</sup>.

Observing the organization of the cosmic web, its regulation and enrichment by galaxies, and the time evolution of these processes will ultimately lead to a better understanding of the past history of the universe and our place in it. There is still much to learn about how galaxies like our own came to be. A deeper understanding can be gained through future observations of the intergalactic medium.

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Figure 7: O VI emission in the cosmic web at z = 0.25 (Bertone et al. 2009). The field of view is approximately 10' x 10'.



-3 -2 -1 0 1 2 3 4 Log<sub>10</sub> flux (photon cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>)