Calling All Baryons

Extremely Low Light Level Observations of the Cosmic Web with Ultra-Large Ground-Based Optical Telescopes

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Outline

Modern astronomy has given us an exciting but eclectic view of the baryonic contents of the high redshift ($z > 2$) universe. Paradoxically, we know most about the very dark and the very bright end of the baryon distribution: At the lowest densities, where most baryons reside, the intergalactic medium has been studied in great detail with QSO absorption lines. At the other end, massive star-forming galaxies have been well-studied in emission. In between these extremes the observational record remains sketchy. Not only are we unable to study what is probably the majority of galaxies, but we are also missing out on some of the most fundamental stages of galaxy formation: the growth of galaxies from gas, and the feedback and return of matter from galaxies into the intergalactic medium. At high redshift, these phenomena are generally too faint to see in emission, and the complex gas-dynamics are difficult to study with one-dimensional QSO sightlines.

The light gathering power of the new generation of 20-30m Giant Segmented Mirror Telescopes (GSMTs) will allow us to examine the relation between galaxies and the intergalactic medium in unprecedented ways. Below we discuss one such approach, observing the high-redshift intergalactic medium and the bulk of star-forming galaxies *in Lyman alpha emission with a large ground-based GSMT*. The study centers on a spectroscopic blind survey of a stretch of sky at redshift ~ 3.

Introduction

Over the past two decades, QSO absorption line spectroscopy with the 6-10m optical telescopes and the almost simultaneous advent of cosmological hydro-simulations have led to considerable progress in our understanding of the intergalactic medium. The puzzle of the nature of the so-called "Lyman alpha forest" and its relation to cosmic large scale structure (e.g., Rauch et al 1998) has essentially been solved. The IGM appears to be a largely smooth cosmic web of filaments and sheets of warm hydrogen and helium gas, photoionized by the ambient cosmic UV background. Theoretical models suggest that the gas is accreting in cold dark matter potential wells and forming galaxies, which return some of their metal-enriched gas, plus thermal, kinetic, and radiative energy back to the IGM. This picture has fundamental implications for galaxy formation, as galaxies are no longer "Island Universes" residing in a vacuum, but are embedded in, feeding off of, and polluting an intergalactic reservoir of baryons that dwarfs them in terms of total mass.

How exactly do galaxies grow, and what is the role of the intergalactic medium ? Even after intensive study with the current generation of telescopes our picture of galaxy formation is still largely incomplete. Most current research into galaxy formation is concerned with the stellar content of galaxies, either studying the evolution of stellar populations or using them as a tracer of galactic dynamics and the underlying dark matter distribution. The question remains as to how galaxies initially form from gas in the intergalactic medium. Theoretical modeling of the gas dynamics of galaxy formation has seen considerable progress over the past decade or so. For example, cosmological hydro-dynamics now suggest that galaxies, depending on their mass and redshift, experience variable fractions of hot and cold accretion (e.g., Keres et al 2005). In principle, this is a testable prediction, but the direct detection of, e.g., cold streams of gas at $z \sim 3$ is still almost impossible with current observational methods.

Our knowledge about galactic outflows has remained similarly patchy. The presence of high redshift winds has been inferred from the metal enrichment of the IGM (e.g., Simcoe et al 2002), from its kinematics (e.g., Rauch et al 2001), and from the energetics of star-bursting galaxies (e.g., Pettini et al 2000, Adelberger et al 2005). But how far out do winds get ? How much of the universe do they pollute, and when ?

Observational results involving gas at high redshift are usually derived from absorption spectroscopy, which provides high sensitivity but only one-dimensional information, making it hard to study a three-dimensional and highly anisotropic process. The gas phases involved are generally low density and low metallicity, and thus difficult to detect in emission.

A Faint Lyman Alpha Glow

We argue here that a ground-based, optical Giant Segmented Mirror Telescope (GSMT) with projected diameters of 20-30m, fitted with a high-throughput, blue/visible spectrograph will open up a new window on studying the IGM and faint galaxies. As proposed by Hogan & Weymann (1987), it is possible, in principle, to see the IGM in emission, observing a direct "image" of the higher density regions of the IGM in the redshifted hydrogen Lyman α line. This idea is based on the fact that neutral hydrogen, when ionized by the UV background recombines and emits Lyman α photons. Hydrogen clouds, once optically thick to ionizing radiation, emit a more or less uniform glow of Lyman α from their outer skin that can be recorded to create a highly detailed image of the cosmic web structures. The strength of the Lyman α line emission is simply proportional to the intensity of the ionizing UV background, yielding, as a bonus, a measurement of that quantity. To be visible in emission, a gaseous object only has to be optically thick to ionizing radiation and does not require internal power sources. Thus we should be able to see even sub-galactic gaseous halos irrespective of stellar content, from the so-called Lyman limit systems onward. The number density of such objects is expected to exceed the number of, e.g., Lyman break selected galaxies at similar redshifts (2-3) by more than two orders of magnitude. Observing them would give us a vastly more complete picture of the cosmic web than possible with a traditional galaxy survey. In reality, the intensity of the expected Lyman alpha radiation would be enhanced beyond the basic signal in higher density regions by other line emission sources like cooling radiation and Lyman alpha induced by internal star-formation. This makes the actual appearance of the universe in Lyman alpha emission more complex than a uniform glow. State-of-the-art theoretical efforts, involving cosmological hydro-simulations that include radiative transfer and incorporate the various sources of Lyman alpha emission, are now starting to predict the details of this more realistic picture (e.g., Kollmeier et al 2009; fig 1).

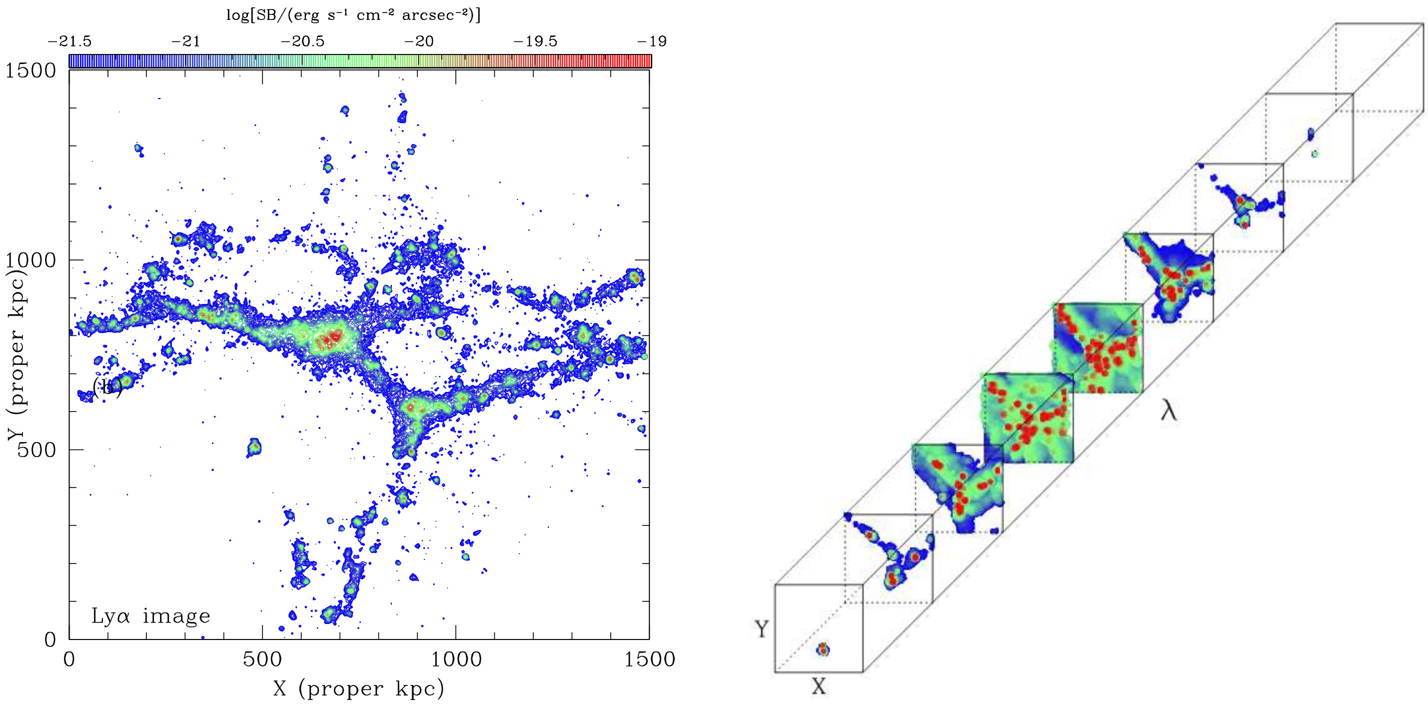

Figure 1: *Left:* Surface brightness of HI Lyman alpha emission from the cosmic web at $z = 3$, from a cosmological simulation incorporating radiative transfer (Kollmeier et al 2009). Many dozens of objects will be detectable in this tiny (cubic) volume, whereas it is barely big enough to contain a single Lyman break galaxy. Even spatial regions below our nominal detection threshold for optically thick gas (see below) can still yield a significant detection, because the large extent of the filamentary gaseous structures on the sky allows for a considerable degree of spatial filtering. The angular size of the box shown here corresponds to only 3.2 arcminutes. The slits of typical, existing wide-field, long-slit spectrographs on large telescopes cover about two to ten times the length of the box, and a typical spectrum, ranging from redshift 2.5 to 3.5 covers about 120 times its depth. *Right:* Channel map from a simulation at $z = 2$, showing how the cosmic web in Lyman alpha emission may appear in an IFU.

Prospects for Detection and Possible Instrumental Setups

The basic Lyman alpha glow effect has been sought by several groups with long slit spectroscopic experiments (e.g., Lowenthal et al 1990; Bunker et al 1998; Rauch et al 2008). So far it has eluded detection, and current estimates of the UV background intensity suggest that the earlier expectations were too optimistic by factors 2-3. The current best guess at the expected signal is a surface brightness $\sim 5\times10^{-20}$erg cm^{-2}s^{-1} per square arcsecond. This value may appear exceedingly faint but it is not beyond reach of a 20m GSMT. An experimental pilot project, using a 92 hour long, spectroscopic longslit exposure with the ESO 8m VLT FORS instrument (Rauch et al 2008; fig. 2) has in fact reached a $1-\sigma$ surface brightness of 8×10^{-20}erg cm^{-2}s^{-1} per square arcsecond, if measured in a 1-arcsecond aperture.

The signal is sky-background-noise-limited and suffers from cosmic surface-brightness dimming.

Thus, a wavelength range extending as far to the blue as instrumentally possible (giving that the ionizing UV background does not drop significantly down to redshift $z \sim 2$) is clearly desirable. Based on these earlier observations, a 130 hour long exposure, with a 20m telescope, a low resolution ($R \sim 1000$), blue-optimized spectrograph with an efficiency of close to 50% and a wavelength range starting just above 3600 Å should allow us to obtain a $5-\sigma$ detection of the Lyman alpha "glow", in a 1 square arcsecond aperture. Since Lyman limit halos are likely to be larger than this by factors of several, this is a conservative estimate of the detectability of the effect.

As we are looking for a signal at a level of less than 1% of a dark sky in the U or B band, suppression of the sky background is of greatest importance. The faintness of the objects naturally rules out broad band imaging, but even the typical existing narrow band searches for bright, galactic Lyman alpha emitters (with band widths on the order of 50Å) admit far too much sky background. Only a spectroscopic method (with the resolution element adapted to the expected line widths, say FWHM $\sim$ 5Å) can achieve the required sky suppression. This still leaves a number of instrumental choices:

The simplest approach is a single long slit in a low resolution spectrograph with a high throughput grating as was used in the ESO pilot program, essentially yielding a pencil-beam survey.

A more coherent volume can be sampled by a slit mask with many parallel long slits, combined with a narrow-band filter to curtail the spectral coverage, creating a quasi-two-dimensional "spectroscopic image". This sort of "Venetian-Blind Spectroscopy" has been used to look for emission in the vicinity of QSOs (Cantalupo et al 2007; Rauch et al, in prep.). Both long slit methods sample a similar volume, although the single long slit spectrum is less prone to cosmic variance and allows for easier detection of foreground interlopers.

Another alternative would be a dedicated integral field unit (IFU) that combines the advantages of a coherent spatial field with a large spectral coverage. Here the tradeoff would be lower efficiency than the methods using traditional slits (fig 1, right panel).

The first detection of the Lyman α glow and a measurement of the cosmic UV background would be possible with a single $\sim$ 130 hour long slit exposure. A truly three dimensional "image" could then be built up either by increasing the sampling with spatial shifts of the long slit masks, or by going to comparable depth with an IFU.

The Faint End of the Galaxy Luminosity Function

Observations deep enough to the see the Lyman alpha glow will be of enormous value for studying the faint end of the galaxy luminosity function and the interactions between galaxies and the surrounding IGM. The pilot project described above yielded detections of a number of faint galaxies (fig. 2) whose Lyman alpha emission is apparently powered by recent star-formation. The number density of these objects is about 25 times that of other classes of star-forming galaxies detected so far from the ground (narrow band surveys of Lyman alpha emitters, e.g., Gronwall et al 2007; or Lyman break galaxies, e.g., Steidel et al 1999).

The large number of objects and the mass function of dark matter halos suggest that this observation is probing galaxy halos with virial velocities down to about 50-70 kms^{-1} (Rauch et al 2008; Barnes & Haehnelt 2009). The strength of the Lyman alpha emission suggests star-formation

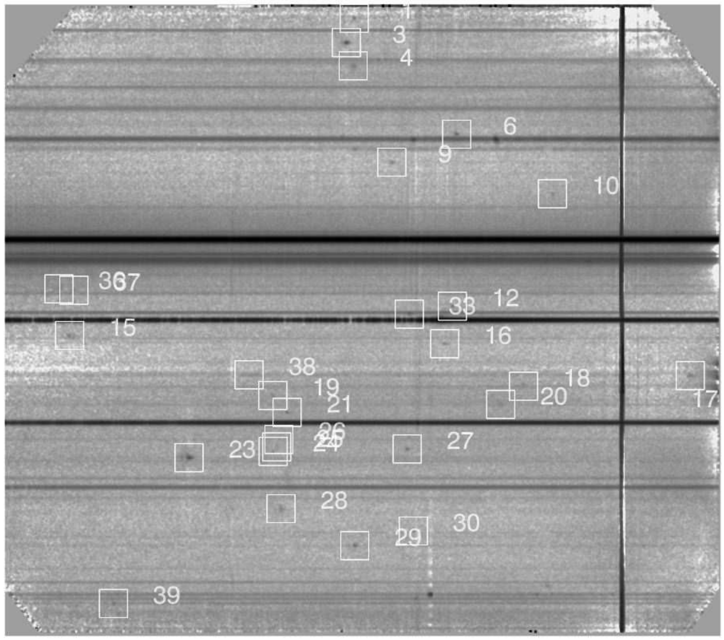

Figure 2: The currently deepest optical spectrum ever taken in extragalactic astronomy. Two-dimensional ("long slit") spectrum of a blank piece of sky, obtained in 92 hours of exposure time with the ESO VLT FORS2 instrument, showing candidates for HI Lyα line emission (boxes). The dispersion direction is horizontal, with blue to the left and red to the right; the spatial direction along the slit is vertical. The length of the slit is about 7 arcminutes. The redshifts covered range from 2.7 to 3.8. The large majority of the continuum traces are foreground lower redshift galaxies and stars.

rates in some cases of less than 1/10 $M_{\odot}\mathrm{yr}^{-1}$, and implied rest-frame-UV continuum luminosities of as low as -16.5. In other words, we are starting to probe dwarf galaxies like the Small Magellanic Cloud at high redshift with a ground-based optical telescope. This conclusion is confirmed by a similar experiment, a preliminary 17 hour long slit spectrum in the Hubble Deep Field, (HDF) with the 10m Keck I telescope and the LRIS instrument (Rauch et al, in prep.; fig. 3). Comparison with the deep imaging of the HDF suggests that the Lyman α emitters identified in the spectroscopic blind search correspond mostly to faint, compact, broad band continuum counterparts at typically 28 magnitudes in the F606W band (or $M_{AB} \sim -17.6$ in the $z \sim 3$ restframe UV continuum), with objects as faint as 29.1 mags showing up in Lyman alpha emission. In other words, with only 17 hours of spectroscopy on a 10m telescope we get almost to the detection limit of the HDF.

It is clear that a GSMT will be able to go far deeper in detecting $z \sim 3$ galaxies than any existing space-based observation (while simultaneously getting spectroscopic redshifts). In particular, an observation going deeper in Lyman alpha luminosity by two magnitudes than the above limits reached by 8-10m telescopes will be able to detect galaxies with virial velocities ~ 30 kms^{-1}, where the suppression of galaxy and star-formation by photoionization pressure may lead to a turn-down or a true "faint end", in the galaxy luminosity function (e.g., Thoul & Weinberg 1996; Kitayama & Ikeuchi 2000; Dijkstra et al 2004). A GSMT may allow us to start seeing all there is, at least in terms of star-forming galaxies !

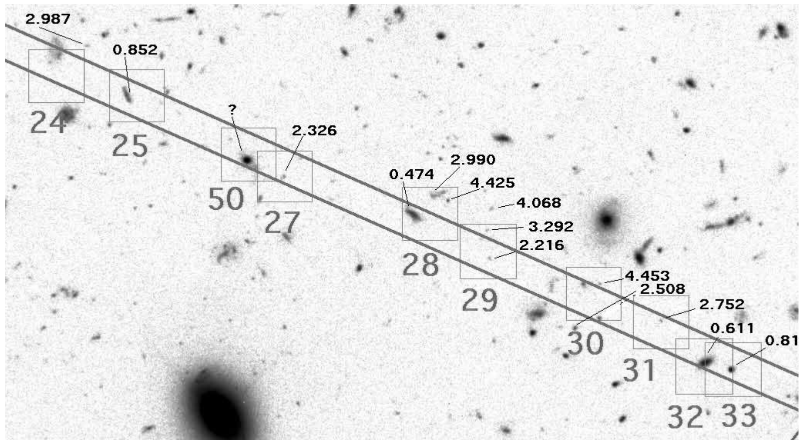

Figure 3: Broad band counterparts of emission line objects in a section of the Hubble Deep Field North (HDFN), as determined from a preliminary long slit experiment with Keck LRIS. All redshifts above z$\sim$2 are based on the Lyα line, lower redshifts rely on [OII], [OIII], and the HI Balmer lines. The two diagonal lines are the approximate outlines of the spectrograph slit. The fact that some objects appear outside of the slit outline is partly a consequence of their Lyα emission being extended and spilling over into the slit. Most objects selected by Lyman alpha line emission are very faint and compact.

Galaxies and the IGM

The spectroscopic observations proposed here will tell us more than the spatial arrangement of galaxies and the IGM. They also provide kinematics information through the velocity profile of the Lyman alpha emission line. Flux densities below 10^{-20} erg cm^{-2} s^{-1} $\mathring{A}$, within reach of a few nights of GSMT time, are sufficient to routinely detect extended galactic Lyman alpha halos around redshift three galaxies (fig. 4) (even though most galaxies appear as point sources in the rest frame UV continuum; see figure 3). Fig. 4 shows four individual objects with extended Lyman alpha halos from the ESO pilot project. In one case the diffuse Lyman alpha emission can be traced out to at least 60 kpc. The anvil-shaped 2-D emission lines look reminiscent of local starburst galaxies (e.g., Mas-Hesse et al 2003). Several of the objects show a blue-red asymmetry in the emission line, indicating (mild) galactic outflows. Detailed modelling of these profiles will help us to understand how far out these winds get, and what fraction of high redshift galaxies of a particular type or luminosity are driving them at any time.

Several of the galaxies in the ESO sample (not shown here) exhibit unusual emission features at even lower flux levels that may be consistent with the predicted infalling cold accretion streams thought to feed baryons to high redshift galaxies (Rauch et al 2008). Confirmation and a larger sample of such cases will definitely have to wait for a large GSMT.

The new generation of large optical telescopes will be able to tackle the nature of *typical* high redshift galaxies and the detailed interactions between galaxies and their gaseous environment. Based on a proof of concept provided by two pilot studies, and the predictions from increasingly

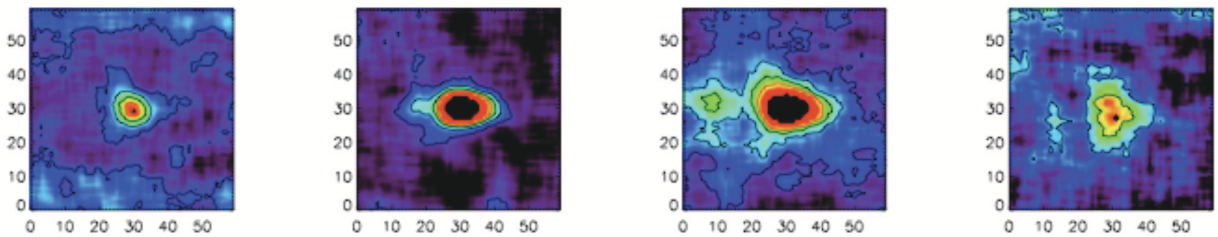

Figure 4: individual $z \sim 3$ Lyman α emission line spectra from the ESO VLT pilot project. Coordinates are in pixel units (0.252 arcsec $\times 0.67 \AA$). The sections of the spectra shown here are 116 proper kpc wide in the spatial direction (vertical) and about 2266 kms^{-1} long in the spectral direction (i.e., horizontally). The areas within the turquoise (light grey) contours have a flux density greater than approximately 1.5×10^{-20} erg cm^{-2} s^{-1} $\AA$.

sophisticated theoretical models we argue that ultra-deep emission line spectroscopy will be one of the most promising applications of a GSMT.

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