Probing the Intergalactic Medium out to the Reionization Epoch

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Scientific category:	OTHER
Instruments:	NIR/SPEC
Days of observation:	10

Abstract

We propose to attempt to determine the epoch at which the intergalactic medium (IGM) was reionized by searching for characteristic spectral features in the redshift-smeared 'Gunn-Peterson' Lyα foreground absorption in the spectra of UV-bright objects uncovered by NGST at $z \gtrsim 5$. If – as is widely anticipated – localized sources such as young galaxies and quasars were responsible for reionizing the IGM, the transition from a neutral to ionized IGM is expected to have taken place in a highly patchy manner, with large pockets of extremely high opacity neutral material appearing in the Lyα absorption at redshifts above the epoch where 'break-through' occurred and the individual HII regions began to overlap. At larger redshifts approaching the neutral era and beyond, a telltale damping wing extending beyond the redmost edge of the Gunn-Peterson trough should appear. This ubiquitous absorption signature should be detectable in NGST spectra having sufficient spectral resolution ($R > 100$) and exposure ($S/N > 10$). A significant unknown for this program is the availability of UV-bright background sources at $z \gtrsim 5$ possessing suitable continuum fluxes shortward of emitted Lyα. Candidates include the likely ionizing sources themselves: young quasars and compact star-forming regions, and supernovae. Some of them will appear brighter because of gravitational lensing. Given their brightness and featureless intrinsic spectra, the afterglows of gamma-ray burst sources may also hold particular promise for this program.

Observing Summary:

Target	RA	Dec	K_{AB}	Configuration/mode	Days
UV SOURCE 1	TBD	TBD	< 29	NIR/SPEC R100	1
UV SOURCE 2	TBD	TBD	< 29	NIR/SPEC R100	1
UV SOURCE 3	TBD	TBD	< 29	NIR/SPEC R100	1
UV SOURCE 4	TBD	TBD	< 29	NIR/SPEC R100	1
UV SOURCE 5	TBD	TBD	< 29	NIR/SPEC R100	1
UV SOURCE 6	TBD	TBD	< 29	NIR/SPEC R100	1
UV SOURCE 7	TBD	TBD	< 29	NIR/SPEC R100	1
UV SOURCE 8	TBD	TBD	< 29	NIR/SPEC R100	1
UV SOURCE 9	TBD	TBD	< 29	NIR/SPEC R100	1
UV SOURCE 10	TBD	TBD	< 29	NIR/SPEC R100	1
				Grand total days	10

Scientific Objectives

The detailed study of intervening absorption in the spectra of high redshift quasars – which can be considered to be the refined version of the original Gunn-Peterson (1965) test – has in recent years provided considerable insight into nature of the intergalactic medium (IGM). In particular, it is now evident that the clouds of hydrogen giving rise to the dense Lyman forest seen in the spectra of all high redshift objects represent only the small residual neutral component of a $\sim 10^4$ times denser highly photoionized intergalactic medium, whose invisible ionized component carries the bulk of the baryons of the universe at high redshift.

This picture of a highly clumpy and photoionized IGM at $z \lesssim 5$ stemming from quasar absorption line studies is in marked contrast with the uniform and near-perfect thermal equilibrium conditions that must have prevailed at higher redshifts $z \sim 10^3$ when the universe recombined and the cosmic microwave background radiation (CMB) decoupled (e.g. Wright et al. 1994). While the highly fluctuating spatial appearance of the Lyman forest can be understood as reflecting the subsequent formation of structure driven by the underlying dark matter (cf. Cen et al. 1994; Zhang, Anninos & Norman 1995; Hernquist et al. 1996), the questions of what caused the intergalactic medium to be reionized and when this event occurred remain largely unanswered. The epoch of reionization marks the end of the "dark ages" during which the cosmic radiation was dominated by the ever-fading CMB at all wavelengths. During this epoch, ionized hydrogen (HII) started to occupy again most of the volume of the universe. Most likely, the phase transition from HI to HII was triggered by the emission from the first stars and quasars in the universe (see complementary DRM program by Loeb & Haiman). The characteristic distance between the sources that ionized the universe was much smaller than the Hubble scale, and the overlap of the HII regions surrounding these sources was completed on a timescale much shorter than the Hubble time. The resulting reionization redshift, z_i, is therefore well defined and serves as an important milestone in the thermal history of the universe. Measurement of this parameter would also constrain the small-scale power of primordial density fluctuations that produced the first objects. Theoretical models and three–dimensional simulations predict that reionization occurs at $7 \lesssim z_i \lesssim 20$, just beyond the horizon of current observations (Haiman & Loeb 1997; Gnedin & Ostriker 1997). NGST is expected to reach the sensitivity required for the detection of sources beyond the reionization redshift, and could probe the properties of the intergalactic medium out to the reionization redshift by detecting transmitted flux between (say) the Lyα and Lyβ absorption troughs in the spectra of sources. Establishing the character of cosmological ionizing sources is an efficient way to constrain competing models for structure formation in the universe, and to study the collapse and cooling of small mass objects at early epochs.

A long-held prime candidate for photoionizing the IGM has been the radiative output of quasars. In this basic picture – which has been explored by numerous authors (Arons & Wigert 1972; Meiksin & Madau 1993; Shapiro, Giroux & Babul 1994; Miralda-Escudé & Rees 1994) – quasars turn on in an initially neutral IGM and give rise to expanding pockets of surrounding ionized material. The universe then rapidly becomes transparent once the
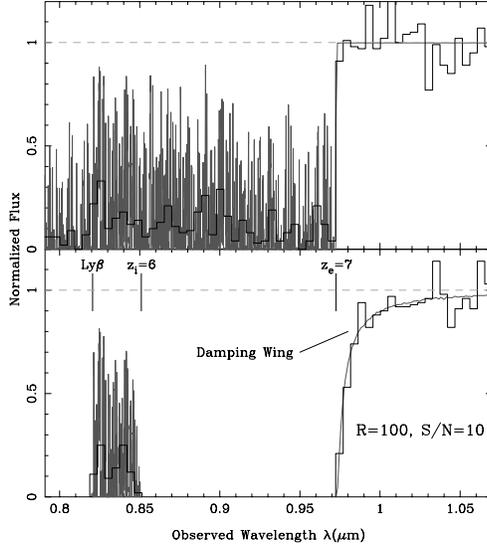
Figure 1: Simulation of the (extrapolated) Lyman forest absorption spectrum out to a redshift of $z_e = 7$ (top frame). The lower frame shows the same absorption spectrum in the case where ionization of the intergalactic medium changes abruptly by a factor 10^4 at a redshift of $z_i = 6$. The thin curves show the true underlying spectra; the overlaid binned curves what would be observed with NGST at $R = 100$ and $S/N = 10$. Note the red damping wing of the absorption trough in the latter case.

individual Strömgren spheres begin to overlap. After 'breakthrough' has been achieved, the ionization is kept maintained by the pseudo-uniform metagalactic radiation field created by the cumulative ionizing output of all subsequent quasars (e.g. Haardt & Madau 1996).

When looking back in redshift, the transition from a neutral to an ionized IGM should manifest itself as a dramatic jump in the net absorption of the Lyman forest, as pockets of still neutral material are encountered and the Lyα absorption transitions to an effectively 'black' ($\tau \sim 10^5$) Gunn-Peterson trough. While no such effect has yet been detected in the Lyα absorption out to $z \sim 5$, an abrupt transition in the ionization of the IGM does appear to be seen in the recent detections of singly ionized HeII $\lambda304$ absorption matching that of the Lyα forest. Although only a few lines of sight have been probed so far, the HeII absorption detected is seemingly black at $z \gtrsim 3.1$ (Jakobsen et al. 1994), finite at $z \lesssim 2.7$ (Davidsen et al. 1996), and patchy at redshifts in between (Reimers et al. 1997). In other words the final stage of reionization of helium from He$^+$ to He^{++} may have occurred as recently as $z \simeq 2.9$, i.e. significantly later than the reionization of hydrogen. Since one expects H and He ionization to occur roughly simultaneously for an ionizing spectrum as energetic as that of quasars, this suggests that hydrogen was already reionized by sources having a softer spectrum – most likely stars – well before the first quasars appeared (Miralda-Escudé & Rees

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1994; Haiman & Loeb 1997).

Several related core NGST proposals are concerned with detecting the first generations of stars and galaxies. The objective of this proposal is to exploit whatever UV bright sources are found as background sources in the hope of pushing the Lyα absorption observations further back in redshift and pin-pointing the epoch of hydrogen reionization.

Figure 1 provides an illustrative simulation of the expected Lyα absorption spectrum toward a background object at $z_e = 7$ in the simple case where reionization occurs abruptly at $z_i = 6$. In this simulation, the Lyman forest was modeled in detail by extrapolating its observed statistical properties to higher redshift, and the reionization was modeled by simply increasing the column densities of all forest clouds at $z > z_i$ by a factor 10^4 representing a plausible ionization level of the forest gas. Since in this relatively low redshift example $\lambda_\beta(1 + z_e) < \lambda_\alpha(1 + z_i)$, a narrow region of (ionized) forest absorption appears between the onset of the (neutral) Lyα and Lyβ absorption troughs. One practical consideration brought out by Figure 1 is that, because the density of intervening absorbers increases rapidly with redshift, the extrapolated Lyman forest is by itself expected to produce very strong absorption at the redshifts of interest when observed at low spectral resolution (residual average transmission $< 10\%$ at $z \simeq 7$). Hence it will require spectra of exceptionally good S/N and background subtraction to detect any remaining pockets of very high opacity neutral material against the ubiquitous forest absorption (as envisaged by Meiksin & Madau 1993). Fortunately, another more readily observable spectral signature of the transition to a neutral IGM is the appearance of the cumulative damping wing of the high column absorption (Miralda-Escudé 1998). This damping wing softens the onset of the Lyα absorption trough and has a simple analytical form that – barring potential complications such as the 'proximity effect' (Bajtlik et al. 1988) and the presence of local damped Lyα absorbers – can be detected by fitting to the normalized continuum. This yields a measure of the true Lyα optical depth in the trough, which in turn is a direct measure of the neutral gas density. Hence, if successful, the detection of the anticipated damping wing will not only provide a the value for z_i, a number that has important bearings on theories of early structure formation (cf. Haiman & Loeb 1997) – but also a direct measure of the baryonic content of the IGM (Miralda-Escudé 1998).

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NGST Uniqueness/Relationship to Other Facilities

The Lyα forest falls within the 1-5 μm core spectral region of NGST for redshifts $7.2 \leq z \leq 40$, which happens to coincide with the likely range for z_i. While the very lowermost portion of this redshift range could conceivably be probed from the ground, it is unlikely that the available UV-bright background objects at these redshifts are bright enough to permit ground-based near-IR spectroscopy at the necessary wavelength coverage, spectral resolution ($R > 100$) and exposure ($S/N > 10$). Thus the bulk of the expected range for z_i is the exclusive domain of NGST.

Observing Strategy

The objective of this program is to measure the depth and profile of the intervening intergalactic Lyα absorption out to progressively larger redshift and determine the redshift beyond which the absorption becomes black and the damping wing of the Gunn-Peterson trough appears. This obviously requires prior knowledge of a sample of suitable background sources covering a range of redshift. From the ground, redshifts out to $z \simeq 5$ have so far been probed using bright quasars as background probes. However, precious little is presently known about the availability of UV-bright sources at redshifts $z \gtrsim 5$. Bright quasars are bound to be extremely rare in view of the rapid decline in the quasar population observed beyond $z \gtrsim 3$. On the other hand, UV-bright objects of some form or another must be present at $z > z_i \gtrsim 5$ since *something* must have reionized the IGM. Clearly, this program will initially have to piggy-back on several other survey-oriented NGST programs aimed at exploring the contents of the universe at $z \gtrsim 5$. These include the planned NGST searches for high redshift galaxies, quasars, supernovae and gamma ray bursts afterglows. For the purposes of this program, not only do the available UV-sources need to be sufficiently bright, they also need to have inherently well-understood spectra in order that intrinsic and intervening spectral features can be disentangled with confidence. This may preclude the use of supernovae due to their complex and heavily blanketed UV spectra. Gamma ray burst afterglows on the other hand display near-perfect featureless spectra – but obviously present numerous other problems in terms of timely identification and scheduling. Another potential complication is the possible presence of local $z_a \approx z_e$ damped Lyα foreground absorption associated with the background sources themselves – the spectral signature of which will be

very difficult to distinguish from that of the damping wing of the Gunn-Peterson trough.

While the contents of the UV universe at the highest redshifts cannot be accurately anticipated before NGST flies, the prerequisite magnitudes of the necessary background sources involved can. As illustrated in Figure 1, the *minimum* spectral resolution and exposure required to hope to detect and measure the damping wing of the Gunn-Peterson trough is $R \simeq 100$ and $S/N \simeq 10$. Assuming a maximum (TAC - limited) exposure time of $t \sim 10^5$ s (i.e. 1 day), the yardstick performance parameters require a minimum source continuum brightness of $F_\nu \gtrsim 10$ nJy ($m_{AB} \lesssim 29$) in the core spectral region. In the (unlikely?) event that $z_i > 40$, so that the Lyα forest region needs to be explored in the thermal IR, this minimum required source brightness increases to $F_\nu \gtrsim 200$ nJy ($m_{AB} \lesssim 25.5$). This program assumes that a number of sources sampling a suitable range in redshift in the core spectral region will be found early on by NGST, and that 10 of these sources will be deemed worthy of detailed spectroscopic follow-on observations. We note that gravitational lensing may be of help in boosting the brightness of some remote sources without adversely affecting their utility for the study of intervening absorption near the emission redshift. A full day of exposure has been allocated to each target regardless of source flux in the hope of improving the spectral resolution and/or exposure beyond the barely sufficient assumed values of $R \simeq 100$ and $S/N \simeq 10$.

◾ Special Requirements

In order to probe the properties of the intergalactic medium down to redshifts as low as 5, it is essential that the wavelength coverage of NGST would extend down to $\sim 6\lambda_\alpha = 0.7\mu$m, where $\lambda_\alpha = 1216$Å is the Lyα wavelength. This program could also involve target-of-opportunity observations should sufficiently high redshift gamma ray afterglows (and to a lesser extent supernovae) turn out to be practical background sources.

Minimum Spectral Resolution: 100 at 2 μm

◾ Precursor/Supporting Observations

High redshift candidates with Lyα emission near and beyond the $z \sim 5$ redshift limit have recently been found with the Keck telescope (Hu, Cowie & McMahon 1998; Dey et al 1998). These sources have been too faint to allow a search for the Gunn-Peterson trough from the ground but could serve as useful follow–up candidates for NGST.

For example, Dey et al. (1998) have recently measured the spectrum of the highest redshift galaxy at z=5.34 with the Keck telescope and found no continuum emission blueward of the rest–frame Lyα wavelength. The authors were able to infer a lower limit of $\tau = 1.2$ on the optical depth of the Lyα forest between 1050 and 1170 Å to z=5.34. NGST could take a much more sensitive spectrum of this object and by that constrain reionization at $z < 5.34$. NGST spectra of similar sources which might be detected over the next decade will provide constraints on reionization at even higher redshifts.