Available online at www.sciencedirect.com
SCIENCE DIRECT®

New Astronomy Reviews 50 (2006) 146–151

New Astronomy Reviews

www.elsevier.com/locate/newastrev

Probing reionization with the cosmological proximity effect and high-redshift supernovae rates

Andrei Mesinger

Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027, United States

Available online 20 December 2005

Abstract

We develop and assess the potential of several powerful techniques, designed to investigate the details of reionization. First, we present a procedure to probe the neutral fraction, $x_{\rm HI}$, using the Lyman α transmission statistics of high-redshift ($z \gtrsim 6$) sources. We find that only tens of bright quasar spectra could distinguish between $x_{\rm HI} \sim 1$ and $x_{\rm HI} \lesssim 10^{-2}$. A rudimentary application of such a technique on quasar SDSS J1030+0524 has yielded compelling evidence of a large neutral fraction ($x_{\rm HI} \gtrsim 0.2$) at $z \sim 6$. We also generate the observable, high-z supernovae (SNe) rates and quantify the prospects of detecting the suppression of star-formation in low-mass galaxies at reionization from such SNe rates, specifically from those obtainable from the James Webb Space Telescope (*JWST*). Our analysis suggests that searches for SNe could yield thousands of SNe per unit redshift at $z \sim 6$, and be a valuable tool at studying reionization features and feedback effects out to $z \lesssim 13$.

Keywords: Cosmology; Theory; Supernovae; Early universe; Quasars

Contents

1. Introduction

The epoch of cosmological reionization is a significant milestone in the history of structure formation. Despite recent observational break-throughs, the details of the reionization history remain poorly determined. The Sloan Digital Sky Survey (SDSS) has detected large regions with no observable flux in the spectra of several $z \sim 6$ quasars (e.g., Fan, 2002). The presence of these Gunn–Peterson (GP) troughs set a lower limit on the volume weighted hydrogen neutral fraction of $x_{\rm HI} \gtrsim 10^{-3}$ (Fan, 2002), implying a rapid evolution in the ionizing background from $z = 5.5$ to $z \sim 6$ (e.g., Fan, 2002), and suggesting that we are witnessing the end of the reionization epoch, with the IGM becoming close to fully neutral at $z \sim 7$. On the other hand, recent results from the Wilkinson Microwave

E-mail address: mesinger@astro.columbia.edu.

1387-6473/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.newar.2005.11.016

Anisotropy Probe (WMAP) have uncovered evidence for a large optical depth to electron scattering, $\tau_e \sim 0.17 \pm 0.04$ (Bennett, 2003) in the cosmic microwave background anisotropies. This result suggests that the universe was already highly ionized at redshifts as high as $z \sim 15$–20. Various feedback mechanisms have been proposed to regulate the evolution of the ionization state of the IGM, with no clear consensus on a favored plausible physical model (e.g., Haiman and Holder, 2003). It is evident that more tools designed to probe the reionization epoch would be of great value in pinning-down the reionization history and increasing our understanding of the early universe.

The rest of this contribution is organized as follows. In Section 2 we discuss how the transmission statistics of high-redshift spectra can be used to place constraints on the neutral fraction and size of HII regions. In Section 3, we describe how the extended dynamical range provided by the Lyman α and Lyman β absorption allowed us to model the gross observed features of quasar SDSS J1030+0524. In Section 4, we predict observable high-redshift SNe rates and asses their usefulness in the detection of reionization features. Finally, in Section 5, we offer our conclusions. Most numerical estimates presented here assume standard concordance cosmological parameters, $(\Omega_\Lambda, \Omega_M, \Omega_b, n, \sigma_8, H_0) = (0.73, 0.27, 0.044, 1, 0.9, 71\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$, consistent with the recent *WMAP* measurements (Spergel, 2003). Unless stated otherwise, all lengths are quoted in comoving units.

2. Mock spectral analysis

In principle, the quasar's absorption spectrum contains a full record of the neutral fraction as a function of position along the line of sight. Since high-redshift sources sit in their own highly ionized Strömgren spheres, the total Lyman α optical depth at a given observed wavelength, λ_{obs}, can be written as the sum of contributions from inside and outside the Strömgren sphere, $\tau_{\mathrm{Ly}\,\alpha} = \tau_R + \tau_D$. These two contributions are shown in Fig. 2, originating from a hydrodynamical simulation (further details of the simulation can be found in Mesinger et al. (2004)). The residual neutral hydrogen inside the Strömgren sphere resonantly attenuates the quasar's flux at wavelengths around $\lambda_\alpha(1+z)$, where $\lambda_\alpha = 1215.67$ Å is the rest-frame wavelength of the Lyman α line center. As a result, τ_R is a fluctuating function of wavelength (solid curve), reflecting the density fluctuations in the surrounding gas. In contrast, the damping wing of the absorption, τ_D, is a relatively smooth function (dashed curve), because its value is averaged over many density fluctuations. The damping wing optical depth is a strong function of the size of the Strömgren sphere, R_S, and the hydrogen neutral fraction outside the Strömgren sphere, x_{HI}.

Although there is a wealth of information in these two components, it is systematically challenging to separate them and hence extract relevant parameters. In Mesinger et al. (2004), we study the feasibility of statistically extracting such parameters from high-redshift spectra. The free parameters in our analysis are R_S and x_{HI}. Note that changing R_S moves the dashed (τ_D) curve left and right, while changing x_{HI} moves this curve up and down in Fig. 2.

The analysis can be summarized as the following. We start with a simulated observed spectrum, generated using a randomly chosen line of sight (LOS) from a cosmological hydrodynamic simulation. Then we guess values for the radius of the Strömgren sphere, R'_S, and the IGM hydrogen neutral fraction, x'_{HI}. Next we approximate the amplitude of the source's intrinsic emission, A', implied by the choices of R'_S and x'_{HI}, using the red side of the Lyman α line where resonance absorption can be neglected. From the observed spectrum, we divide out the assumed intrinsic emission ($A' \times$ *known spectral shape*), and the assumed damping wing flux decrement, $e^{\tau_D(\lambda_{\mathrm{obs}}, R'_S, x'_{\mathrm{HI}})}$, calling the result $S'(\lambda_{\mathrm{obs}})$. If our choices of R'_S and x'_{HI} were correct, $S'(\lambda_{\mathrm{obs}})$ should represent the resonance absorption flux decrement alone. Hence, we compare a histogram of the implied resonance optical depths, $-\ln[S'(\lambda_{\mathrm{obs}})]$, to the known histogram of resonance optical depth (obtained from the simulation). We then repeat this procedure with different choices of R'_S and x'_{HI}, finding the ones whose implied resonance optical depths most closely match the known histogram.

A few of the resulting histograms are shown in Fig. 1. The template distribution of resonance optical depths obtained from our simulation is shown in the top left panel. Distributions derived from our inversion analysis explained above are shown in the other panels, with the correct parameter choice in the top right and incorrect choices in the bottom two panels. We test the hypothesis that the

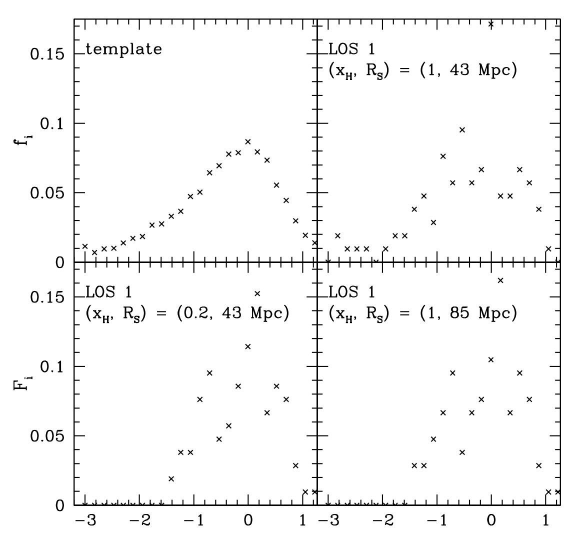

Fig. 1. Histogram of the template distribution τ_R (*top left*), and histograms of the derived τ'_R distribution: $(x_{\mathrm{HI}}, R_S) = (1{,}43\ \mathrm{Mpc})$ (correct values) (*top right*), $(x_{\mathrm{HI}}, R_S) = (0.2{,}43\ \mathrm{Mpc})$ (*bottom left*), $(x_{\mathrm{HI}}, R_S) = (1{,}85\ \mathrm{Mpc})$ (*bottom right*). We test the hypothesis that the top right, bottom left and bottom right histograms (among many others in parameter space) were drawn from the distribution in the top left. We find that the top right panel is consistent with being drawn from the distribution in the top left, and that the bottom panels are not.