Mem. S.A.It. Vol. 88, 854
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Memorie della

Accurate determination of radiation damped profiles in the reionization epoch

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Abstract. Combining accurate scattering theory and standard cosmology, we investigate intrinsic model profiles for extremely high column density neutral hydrogen systems near the epoch of reionization. When the neutral column density reaches $N_{\rm HI} \sim 10^{22}\,{\rm cm}^{-2}$, the classical approximations can not describe radiation damped profile properly. Based on the second-order perturbation theory, we accurately computed the intrinsic Lyman scattering cross-sections. Employing the Monte Carlo method to random distribution of Lyα absorbers in the post-reionization region, we quantitatively examined the impact of inhomogeneous redshift distribution on transmission profiles.

1. Introduction

The ionization history of the intergalactic hydrogen provides invaluable information about the early evolution of the universe. The presence of neutral hydrogen during the epoch of reionization causes a severe flux drop in the transmission profiles of the first luminous sources (Gunn & Peterson 1965). With the high oscillator strength, a small remnant of neutral hydrogen in the post-reionization region can considerably increase Lyα opacity (Loeb & Barkana 2001; Fan et al. 2006). Due to the locality of luminous sources and the complex geometry of the IGM distribution, reionization process is highly inhomogeneous (Mesinger et al. 2003; Becker et al. 2015). In this study, we present transmission profiles considering accurate scattering theory and inhomogeneous redshift distribution.

2. Transmission profiles

Radiation damping is intrinsic to the photon-atom interaction. When innumerable absorbers lie along the line of sight, the line center is seriously saturated and the broad damping wing develops. The classical approximations can not properly represent radiation damped profiles of the extremely high column density systems $N_{\rm HI} \sim 10^{22}\,{\rm cm}^{-2}$ (Lee 2003). The time-dependent second-order perturbation theory provides a detailed description for radiation damping phenomena (Bach & Lee 2015). In our calculation, the second-order scattering theory for all Lyman transitions including the inelastic effect of the Raman scattering (Lee 2013) has been incorporated. In the previous theoretical study on the Gunn-Peterson troughs, Haiman & Loeb (1999) introduced the absorption effect by the random distribution of Lyα clouds based on the Monte Carlo simulations. Later, Bach (2017) combined the

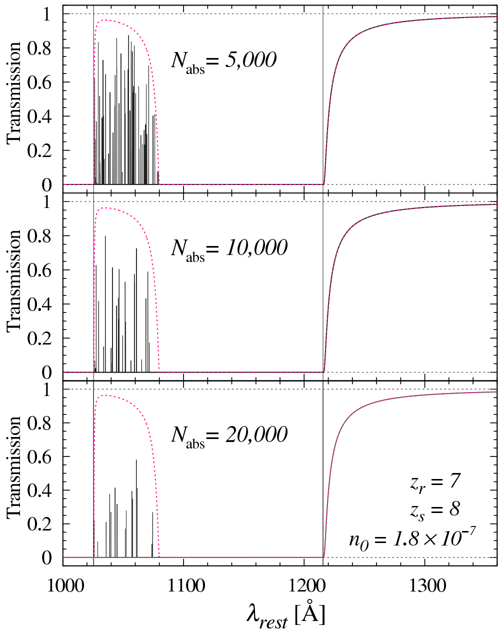

Fig. 1. Applying the Monte Carlo simulation to a random distribution of the Lyα clouds in the mostly ionized region ($z \leq 7$), fractional transmission profiles have been generated. The number of Lyα absorbers is set to be $N_{abs} = 5,000$ (*top*), $10,000$ (*middle*). and $20,000$ (*bottom*) in the redshift interval $6 \leq z \leq 7$.

second-order scattering theory and inhomogeneous IGM distribution. Similarly, we generate a random velocity fields of the neutral hydrogen patch, and then we quantitatively examine the impact of local absorption on the transmission profiles.

Adopting recent cosmological parameters $(\Omega_\Lambda,\ \Omega_M,\ \Omega_b,\ h) = (0.72,\ 0.28,\ 0.046,\ 0.7)$ (Hinshaw et al. 2013) and the comoving number density of atomic hydrogen $n_0 = 1.8 \times 10^{-7}\ {\rm cm}^{-3}$, the transmitted flux is computed (Fig.1). We assume that a luminous source is located at $z_s = 8$ and reionization is completed at $z_r = 7$. The *solid* line corresponds to the simulated absorption spectra affected by the discrete Lyα clouds (N_{abs}=5000, 10000, 20000) in the interval $6 \leq z \leq 7$. Peculiar velocities of local absorbers are adjusted by the Doppler parameters $b_0 = 10 - 35\,{\rm km\,s^{-1}}$ and the local neutral hydrogen fractions in the ionized region are set to be $f_{\rm HI} = 10^{-3} - 10^{-5}$. The *dotted* line denotes the Lyα trough without additional absorption in the post-reionization region. For simplification, metal absorption and the lower redshift Lyα clouds ($z < 6$) are neglected.

3. Discussion

Fundamentally, the shape of the individual Lyman cross-section is asymmetric due to involvement of infinitely many level transitions. This intrinsic skewness of each line profile should be accounted to accurately define the high column density systems. Unfortunately, the blue damping wing of Lyα trough is desperately blocked by the residual neutral patches in the post-reionization region, and the red damping wing barely provides information of near-source distribution. If this serious extinction is cautiously subtracted, transmitted flux between Lyα and Lyβ will provide a better constraint on the ionized state near the epoch of reionization.

Acknowledgements. This research was supported by Basic Science Research Programme (2017-11-0297) through the National Research Foundation of Korea(NRF) funded by the Ministry of Education. KB gratefully acknowledges computational support from the KASI-Yonsei joint research programme.

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