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Cosmological reionization

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Abstract. The study of reionization has acquired increasing significance recently because of various reasons. On the observational front, we now have good quality data of different types at high redshifts. Theoretically, the importance of the reionization lies in its close coupling with the formation of first cosmic structures, and there has been much progresses in modeling the process. In this article, we will review and discuss the possibility of constraining the reionization history by matching theoretical models with observations.

Keywords : cosmology: large-scale structure of Universe – galaxies: intergalactic medium

1. Introduction

In the framework of the hot big bang model, the baryonic matter in the Universe is expected to become almost neutral after the recombination epoch at $z \sim 1100$. Given the fact (known from observations of quasar absorption spectra) that the Universe is highly ionized at $z < 6$, it is crucial to understand as to when and how did the luminous sources reionize the Universe. Recently, the interest in cosmological reionization has received a big boost, thanks to the availability of a variety of data sets. These observations suggest that the reionization occurred somewhere between $z \sim 6 - 15$, and that the nature of this process is quite complex. Furthermore, it is also quite clear that the reionization process is very closely coupled to the formation of galaxies and other structures (Choudhury 2009).

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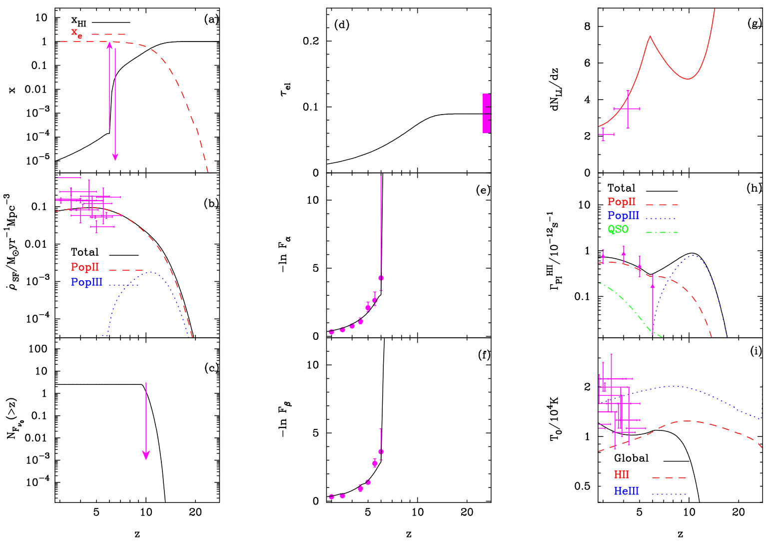

Figure 1. Comparison of model predictions with observations for the best-fit model. The different panels indicate: (a) The volume-averaged neutral (solid line) and ionized (dashed line) hydrogen fraction. (b) SFR for different stellar populations. (c) The number of source counts above a given redshift. (d) Electron scattering optical depth. (e) Ly α effective optical depth. (f) Ly β effective optical depth. (g) Evolution of Lyman-limit systems. (h) Photoionization rates for hydrogen. (i) Temperature of the mean density IGM.

2. Semi-analytical modeling of reionization

We now discuss a semi-analytical model (Choudhury & Ferrara 2005, 2006) which implements most of the relevant physics governing reionization, such as the IGM density distribution, three different classes of ionizing photon sources (massive PopIII stars, PopII stars and QSOs), chemical feedback for PopIII $\rightarrow$ PopII transition and radiative feedback suppressing star formation in low-mass galaxies. The best-fit model is found to be consistent with a variety of available data shown in Figure 1.

3. Implications of the model

According to the best-fit parameters for our model, hydrogen reionization starts around $z = 15$, driven by the metal-free stars (with normal Salpeter-like IMF), and is 90% complete by $z \approx 10$. The photoionizing power of PopIII stars fades for $z \lesssim 10$ because of the concomitant action of radiative and chemical feedback, which causes the reionization process to stretch considerably and to end only by $z \approx 6$.

Interestingly, scenarios which do not include halos with $M < 10^9 M_\odot$ fail at reproducing the Gunn-Peterson and electron scattering optical depths simultaneously,

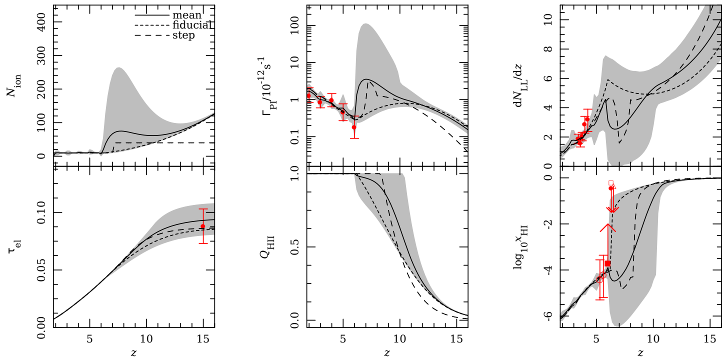

Figure 2. The marginalized posteriori distribution of various quantities obtained from the PCA. The solid lines correspond to the model described by mean values of the parameters while the shaded regions correspond to 2-σ limits. *Top-left:* the effective $N_{\rm ion}(z)$; *Top-middle:* the hydrogen photoionization rate; *Top-right:* the Lyman-limit system distribution; *Bottom-left:* the electron scattering optical depth; *Bottom-middle:* the volume filling factor of ionized regions; *Bottom-right:* the global neutral hydrogen fraction.

as they contribute too few (many) photons at high (low, $z \sim 6$) redshift (Choudhury, Ferrara & Gallerani 2008). Reionization in the large-galaxies-only scenario can remain viable only if metal-free stars and/or some other exotic sources at $z > 6$ are included.

We find that more than 80% of the ionizing power at $z \geq 7$ comes from small mass halos harbouring metal-free (PopIII) stars (Choudhury & Ferrara 2007). We conclude that $z > 7$ sources tentatively identified in broad-band surveys are relatively massive ($M \sim 10^9 M_\odot$) and rare objects which are only marginally ($\sim 1\%$) adding to the reionization photon budget.

The Ly α absorption spectra of QSOs at $z \approx 6$ show wide regions of zero transmission which have been interpreted as signatures of large neutral hydrogen fractions. We have used our semi-analytical models to show that the reionization history can be well-constrained by the distribution of dark gap widths in the absorption spectra at $z > 6$ (Gallerani, Choudhury & Ferrara 2006). By comparing the statistics of these spectral features with our model, we conclude that the neutral hydrogen fraction $x_{\rm HI}$ evolves smoothly from $10^{-4.4}$ at $z = 5.3$ to $10^{-4.2}$ at $z = 5.6$, with a robust upper limit $x_{\rm HI} < 0.36$ at $z = 6.3$ (Gallerani et al. 2008a). In addition, we show that the observation of GRB 050904 strongly favours a highly ionized intergalactic medium at $z \sim 6$, with an estimated $x_{\rm HI} = (6.4 \pm 0.3) \times 10^{-5}$ (Gallerani et al. 2008b).

We have applied our model to constrain the effects of feedback using 21cm signal at high redshifts (Schneider et al. 2008), CMBR polarization data (Burigana et al. 2008) and the galaxy luminosity function in overdense regions at $z \approx 8$ (Kulkarni & Choudhury 2011). Also, our model predictions for the intergalactic radiation fields at very high redshifts can be constrained through the absorption of high-energy gamma-rays, which will leave signatures in the spectra of blazars or GRBs (Inoue et al. 2010).

4. Model-independent constraints on reionization

A different approach in constraining reionization would be to study it in a model-independent manner. In order to achieve this, we extend our model to obtain the observational constraints on reionization via a principal component analysis (PCA). Assuming that reionization at $z > 6$ is primarily driven by stellar sources, we decompose the unknown function $N_{\rm ion}(z)$, representing the number of photons in the IGM per baryon in collapsed objects, into its principal components and constrain the latter using the photoionization rate obtained from Ly α forest Gunn-Peterson optical depth, the WMAP7 electron scattering optical depth and the redshift distribution of Lyman-limit systems at $z \sim 3.5$ (Mitra, Choudhury & Ferrara 2011). We find that there is a clear indication that $N_{\rm ion}(z)$ must increase at $z > 6$ (see Figure 2), thus ruling out reionization by a single stellar population with non-evolving IMF, and/or star-forming efficiency, and/or photon escape fraction. The PCA implies that reionization must be 99% completed between $5.8 < z < 10.3$ (95% confidence level) and is expected to be 50% complete at $z \approx 9.5 - 12$.

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