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Cosmic density field reconstruction from Lyα forest data

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ABSTRACT

We present a novel, fast method to recover the density field through the statistics of the transmitted flux in high-redshift quasar absorption spectra. The proposed technique requires the computation of the probability distribution function of the transmitted flux ($P_{\rm F}$) in the Lyα forest region and, as a sole assumption, the knowledge of the probability distribution function of the matter density field (P_Δ). We show that the probability density conservation of the flux and matter density unveils a flux–density (F–Δ) relation which can be used to invert the Lyα forest without any assumption on the physical properties of the intergalactic medium. We test our inversion method at $z = 3$ through the following steps: (i) simulation of a sample of synthetic spectra for which P_Δ is known; (ii) computation of $P_{\rm F}$; and (iii) inversion of the Lyα forest through the F–Δ relation. Our technique, when applied to only 10 observed spectra characterized by a signal-to-noise ratio ≥ 100, provides an exquisite (relative error $\epsilon_\Delta \lesssim$ 12 per cent in $\gtrsim$50 per cent of the pixels) reconstruction of the density field in $\gtrsim$90 per cent of the line of sight. We finally discuss strengths and limitations of the method.

Key words: intergalactic medium – quasars: absorption lines – large-scale structure of Universe.

1 INTRODUCTION

The ultraviolet radiation emitted by a quasar can suffer resonant Lyα scattering as it propagates through the intergalactic neutral hydrogen. In this process, photons are removed from the line of sight (LOS) resulting in an attenuation of the source flux, the so-called Gunn–Peterson effect (Gunn & Peterson 1965). At $z \sim 3$, the neutral hydrogen number density is sufficiently small to allow to resolve the wide series of absorption lines, which give rise to the so-called Lyα forest in quasar absorption spectra. Initially, the absorption lines observed in quasar spectra were believed to be produced by an intergalactic population of pressure-confined clouds, photoionized by the integrated quasar flux (Sargent et al. 1980). Nowadays, absorbers of the Lyα forest are generally associated to large-scale neutral hydrogen density fluctuations in the warm photoionized intergalactic medium (IGM).

This scenario, first tested through analytical calculations (Bond, Szalay & Silk 1988; Bi, Börner & Chu 1992), has received an increased consensus, thanks to the detection of a clustering signal along both individual (Cristiani et al. 1995; Lu et al. 1996; Kim et al. 2001) and close pairs of quasar LOS, resulting in an estimated size for the absorbers which varies between few hundreds of kpc (Smette et al. 1992; D'Odorico et al. 1998; Rauch et al. 2001; Becker, Sargent & Rauch 2004) to few Mpc (Rollinde et al. 2003; Coppolani et al. 2006; D'Odorico et al. 2006). Hydrodynamical cosmological simulations lend further support to this picture, having established the existence of a tight connection between the H I density field and the dark matter distribution, at least on scales larger than the Jeans length of the IGM (Cen et al. 1994; Petitjean, Mücket & Kates 1995; Zhang, Anninos & Norman 1995; Hernquist et al. 1996; Miralda-Escudé et al. 1996). As a consequence of this result, the Lyα forest has been proposed as a powerful method to study the clustering properties of the dark matter density field and to measure its power spectrum (Croft et al. 1998; Nusser & Haehnelt 1999, hereinafter NH99; Pichon et al. 2001; Rollinde, Petitjean & Pichon 2001; Viel, Haehnelt & Springel 2004; McDonald et al. 2005; Zaroubi et al. 2006; Saitta et al. 2008; Bird et al. 2010).

In this Letter, we focus our attention on the reconstruction of the density field along the LOS, which represents the starting point for the dark matter power spectrum measurement. We present a novel, fast method to recover the density field along the LOS towards a $z \sim 3$ quasar which can be considered alternative and/or complementary to the existing techniques in the literature mentioned above which will be further discussed in this work.

2 MODELLING THE FOREST

Let us discretize the LOS towards a distant quasar in a number of pixels $N_{\rm pix}$. The transmitted flux due to the Lyα absorption in the IGM at a given pixel i is computed from the usual relation

$$F(i) = {\rm e}^{-\tau(i)}, \quad (1)$$

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where $\tau(i)$ is the Lyα absorption optical depth:

$$\tau(i) = cI_\alpha \frac{\Delta x}{1+z(i)} \sum_{j=1}^{N_{\rm pix}} n_{\rm H\,I}(j)\Phi_\alpha[v_{\rm H}(i) - v_{\rm H}(j)]\,, \qquad (2)$$

where c is the light speed, I_α is the Lyα cross-section, Δx is the comoving pixel size, $z(i)$ is the redshift of pixel i, Φ_α is the Voigt profile for the Lyα transition, $v_{\rm H}$ is the Hubble velocity[1] and $n_{\rm H\,I}$ is the neutral hydrogen fraction.

The computation of $n_{\rm H\,I}$ generally assumes that the low-density gas which gives rise to the Lyα forest is approximately in local equilibrium between photoionization and recombination. By neglecting the presence of helium, and assuming that the IGM is highly ionized at the redshift of interest by a uniform ultraviolet background, the photoionization equilibrium condition provides us with the following relation:

$$n_{\rm H\,I}(j) = \frac{\alpha[T(j)]}{\Gamma}\{n_0[1+z(j)]^3\Delta(j)\}^2 \propto \Delta(j)^\beta\,, \qquad (3)$$

with $1.5 < \beta < 2.0$ (Hui & Gnedin 1997). In equation (3), Γ is the photoionization rate of neutral hydrogen at a given redshift $z(j)$, $\Delta(j)$ is the overdensity at pixel j, n_0 is the mean baryon number density at $z = 0$ and $\alpha[T(j)] \propto T(j)^{-0.7}$ is the temperature-dependent radiative recombination rate. For quasi-linear IGM, where non-linear effects like shock-heating can be neglected, the temperature can be related to the baryonic density through a power-law relation (Hui & Gnedin 1997):

$$T(j) = T_0\Delta(j)^{\gamma-1}\,, \qquad (4)$$

where T_0 is the IGM temperature at the mean density at a given redshift $z(j)$ which depends on the reionization history of the Universe, such as the slope γ of the equation of state, and Γ.

Besides the $n_{\rm H\,I}$ computation, the thermal state of the IGM affects the profile of the absorption lines. In fact, the Voigt profile which enters in equation (2) is the convolution of a Gaussian and a Lorentzian profile, since it takes into account the thermal and the natural broadening of the absorption line, respectively. For low-column-density regions, as the ones corresponding to the Lyα forest, thermal broadening dominates and the Voigt function reduces to a simple Gaussian

$$\Phi_\alpha[v_{\rm H}(i) - v_{\rm H}(j)] = \frac{1}{\sqrt{\pi}b(j)} \exp\left\{-\left[\frac{v_{\rm H}(i) - v_{\rm H}(j)}{b(j)}\right]^2\right\}\,, \qquad (5)$$

whose width is set by the temperature-dependent Doppler parameter $b(j) = \sqrt{2k_{\rm B}T(j)/m_{\rm p}}$, with $k_{\rm B}$ and $m_{\rm p}$ being the Boltzmann constant and the proton mass, respectively.

From the system of equations (1)– (5), the complex relation between the transmitted flux F in quasar absorption spectra and the underlying density field Δ becomes evident. The determination of the F–Δ relation not only depends on the parameters describing the physical state of the IGM (Γ; T_0; γ), that is, on the cosmic reionization history, but also depends on the convolution of the resulting $n_{\rm H\,I}$ with the profile of the absorption lines, which in turn is linked to the thermal state of the gas through the Doppler parameter b. In the next section, we describe how the F–Δ relation can be efficiently inferred from a statistical analysis of the transmitted flux in quasar absorption spectra.

[1] The velocity of a Lyα forest absorber is generally given by the sum of the Hubble and the peculiar velocities, that is, $v(i) = v_{\rm H}(i) + v_{\rm pec}(i)$. In this work, we neglect peculiar velocities and we discuss this issue in the Discussion section.

3 FLUX–DENSITY RELATION

Let us assume that the signal-to-noise ratio (S/N) characterizing an observed quasar absorption spectrum is such that the maximum flux (minimum optical depth) which can be distinguished from full transmission is given by $F_{\rm max}(\tau_{\rm min})$ and that the minimum detectable flux (maximum optical depth) is given by $F_{\rm min}(\tau_{\rm max})$. By combining equations (2)–(4), it results that $\tau = \tau(z, \beta, \Gamma, T_0, \gamma, \Delta)$. This means that, at a given redshift z, for any β, and for any given IGM thermal and ionization history, two characteristic overdensities do exist: (i) $\Delta_{\rm b}$, where the subscript 'b' means 'bright', such that each Lyα absorber sitting on $\Delta < \Delta_{\rm b}$ would provide $\tau(\Delta_{\rm b}) \lesssim \tau_{\rm min}$, that is, full transmission of the quasar continuum ($F > F_{\rm max}$); and (ii) $\Delta_{\rm d}$, where the subscript 'd' means 'dark', such that each overdensity $\Delta > \Delta_{\rm d}$ would provide $\tau(\Delta_{\rm d}) \gtrsim \tau_{\rm max}$, therefore completely depleting the flux emitted by the source at the location of the absorber ($F < F_{\rm min}$).

One of the statistics adopted to analyse quasar spectra is the probability distribution function of the transmitted flux ($P_{\rm F}$), which quantify the number of pixels characterized by a transmitted flux between F and $F + {\rm d}F$. Let us assume that at a given overdensity, Δ_*, it is associated a unique value of the transmitted flux F_*. In this case, $\Delta_{\rm b}$ and $\Delta_{\rm d}$ can be defined through the probability of finding a pixel characterized by a transmitted flux $F > F_{\rm max}$ and $F < F_{\rm min}$, respectively. Once $P_{\rm F}$ is computed from observed spectra, $\Delta_{\rm b}$ and $\Delta_{\rm d}$ can be determined from the following equations:

$$\int_{F_{\rm max}}^{1} P_{\rm F}\,{\rm d}F = \int_0^{\Delta_{\rm b}} P_\Delta {\rm d}\Delta\,, \qquad (6)$$

$$\int_0^{F_{\rm min}} P_{\rm F}\,{\rm d}F = \int_{\Delta_{\rm d}}^{+\infty} P_\Delta {\rm d}\Delta\,, \qquad (7)$$

where P_Δ is the probability distribution function of the density field. Analogously to equations (6) and (7), to each pixel characterized by a transmitted flux $F_{\rm min} < F_* < F_{\rm max}$ an overdensity $\Delta_{\rm b} < \Delta_* < \Delta_{\rm d}$ can be associated such that

$$\int_{F_*}^{F_{\rm max}} P_{\rm F}\,{\rm d}F = \int_{\Delta_{\rm b}}^{\Delta_*} P_\Delta {\rm d}\Delta \qquad (8)$$

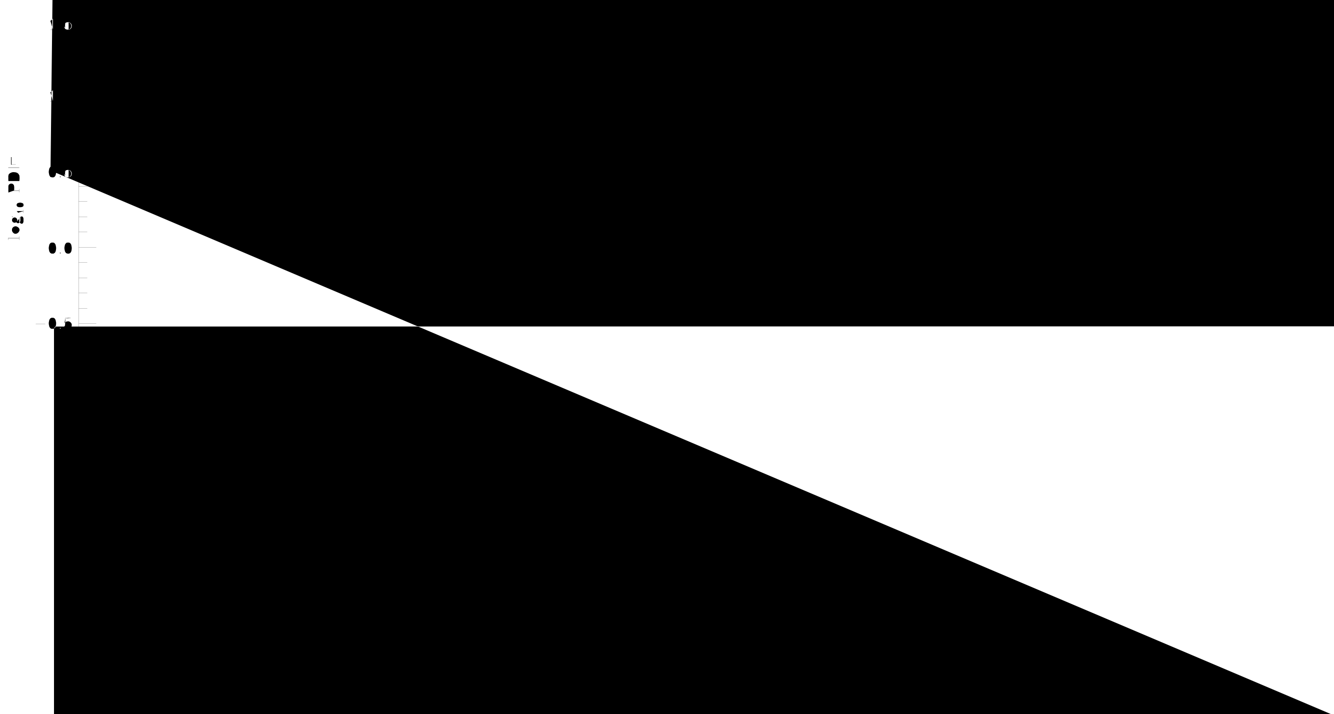
or, equivalently,

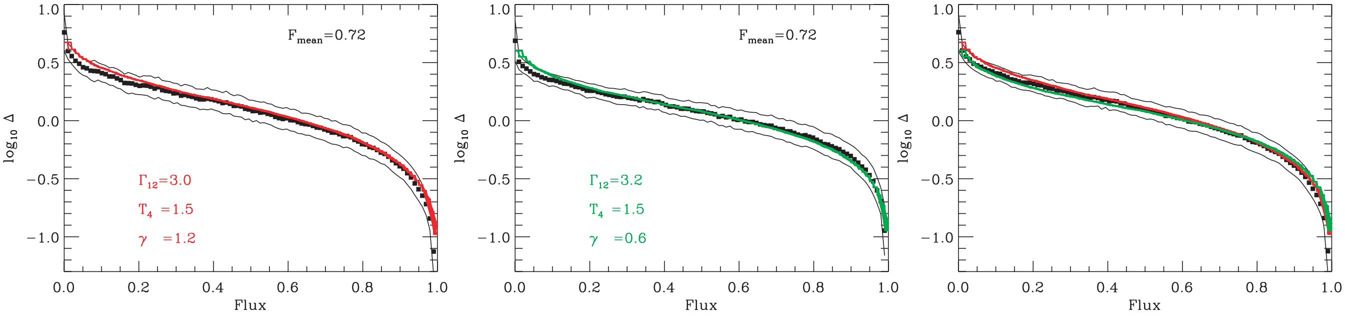
$$\int_{F_{\rm min}}^{F_*} P_{\rm F}\,{\rm d}F = \int_{\Delta_*}^{\Delta_{\rm d}} P_\Delta {\rm d}\Delta. \qquad (9)$$

Note that equations (6)–(9) are simply obtained by imposing the conservation of the flux/density probability densities. The inference of $\Delta_{\rm b}$, $\Delta_{\rm d}$ and Δ_* only depends on the assumed P_Δ and not on any assumption concerning thermal and ionization histories which are, however, encoded into the observed $P_{\rm F}$, as we show in the next section. By solving equation (8), for each observed value of F_* in terms of Δ_*, the F–Δ relation of the Lyα forest can be readily derived. Such F–Δ relation can be used to invert the Lyα forest, therefore allowing to reconstruct the density field along the LOS.

4 INVERSION PROCEDURE

We simulate quasar absorption spectra at $z = 3$ through the model described in the previous section. In particular, for what concerns the baryonic density distribution along the LOS entering in equation (3), we adopt the method described by Gallerani, Choudhury & Ferrara (2006), whose main features are summarized as follows. The spatial distribution of the baryonic density field and its correlation with the peculiar velocity field are taken into account adopting the formalism





1.0
0.5
0.0
−0.5
−1.0
$\log_{10} \Delta$
0.0
0.2
0.4
0.6
0.8
1.0
Flux
F_{mean}=0.72
Γ_{12}=3.0
T_4 =1.5
γ =1.2
F_{mean}=0.72
Γ_{12}=3.2
T_4 =1.5
γ =0.6

flux to the underlying density field and then invert this relation. As shown in Section 2, any model which allows to predict the transmitted flux resulting from a given density field distribution, at a given redshift z, depends on several uncertain parameters (β, Γ, T_0 γ). This approach has been pioneered by NH99. These authors have developed a technique based on a model of the Lyα forest, which allows to reconstruct the density field along quasar sightlines through an iterative method. Such technique allows to correctly take into account the thermal broadening of the absorption lines, assuming that both T_0 and γ, which affect the Doppler parameter, are known.

The NH99 inversion method has been adopted by several authors to study the properties of the IGM and to measure the matter power spectrum from the Lyα forest (e.g. Pichon et al. 2001; Rollinde et al. 2001; Zaroubi et al. 2006). However, it has been recognized that uncertainties on β, γ and T_0 result in spurious biases in the recovered density field (NH99; Pichon et al. 2001; Rollinde et al. 2001). The strong dependence of the matter power spectrum on the IGM properties, as inferred from Lyα forest data, has been also confirmed by Bird et al. (2010). Saitta et al. (2008) have proposed another possible approach to reconstruct the density field through the transmitted flux in quasar absorption spectra, named FLO (i.e. From Lines to Overdensities). Also in this case the parameters defining the IGM equation of state need to be assumed. Moreover, while the FLO method seems promising for the reconstruction of the most-overdense regions (up to $\Delta \sim 30$), underdensities ($\Delta < 1$) tend to be underestimated.

Summarizing, the methods available so far in the literature tried to invert the F–Δ relation for which a large number of assumptions have to be made on the physical state of the IGM. We have shown that the F–Δ relation can be efficiently inferred from a *statistical* analysis of the transmitted flux in quasar absorption spectra by drastically reducing the number of assumptions. As far as this work is concerned, we have not considered peculiar velocity effects which influence the quality of the recovery (NH99). However, we note that the same method as described in NH99 for the reconstruction in real space can be applied to our recovered density field iteratively. We leave this to a future work. We finally note that so far we have been referring to quasar absorption spectra. However, the method proposed can be applied to gamma-ray burst absorption spectra as well.

6 CONCLUSIONS

A novel, fast method to recover the density field through the statistics of the transmitted flux in high-redshift quasar absorption spectra has been introduced. The proposed technique requires the computation of the probability distribution function of the transmitted flux ($P_{\rm F}$) in the Lyα forest region and, as a sole assumption, the knowledge of the probability distribution function of the matter density field (P_Δ). We have shown that the probability density conservation of the flux and matter density unveils a F–Δ relation which can be used to invert the Lyα forest, without any assumption on the properties of the IGM.

Our inversion method has then been tested at $z = 3$ through a semi-analytical model of the Lyα forest which adopts a lognormal P_Δ. First of all we have simulated a sample of synthetic spectra varying the properties of the IGM (Γ; T_0; γ) in such a way that the resulting mean transmitted flux matches observations. Then, we have computed $P_{\rm F}$ for each parameter set considered. Different IGM properties affect differently the $P_{\rm F}$, hence resulting in slightly different F–Δ relations. This provides a reconstruction method which does not require *any assumption* on the thermal and ionization states of the IGM. The proposed method is particularly suitable for the extraction of large-scale matter density field signals from Lyα data, which represents the starting point for the detection of baryonic acoustic oscillations through quasar absorption spectra (McDonald & Eisenstein 2007; Slosar et al. 2009; Kitaura, Gallerani & Ferrara 2010). In fact, this kind of studies are based on the density field reconstruction on scales smaller than 0.1 Mpc along a large number of LOS more than 10 Mpc long. Such requirements are beyond the capability of current simulations, while can be satisfied through our fast, though approximate, technique.

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