The Epoch of Structure Formation in Blue Mixed Dark Matter Models

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1 June 1995

ABSTRACT

Recent data on high-redshift abundance of damped Lya systems are compared with theoretical predictions for 'blue' (i.e. \( n > 1 \)) Mixed Dark Matter models. The results show that decreasing the hot component fraction \( \Omega_b \) and/or increasing the primordial spectral index \( n \) implies an earlier epoch of cosmic structure formation, thus widening the range of allowed parameters in the framework of this scenario.

1 INTRODUCTION

From a long time observations of high-redshift objects have become a potentially powerful constraint for models of cosmic structure formation. The availability of statistically reliable samples of quasars allowed to address this problem in a quantitative way in the framework of the Cold Dark Matter cosmogony (Efstathiou & Rees 1988; Huchmct 1993). Moreover, the comparison of predictions and observations of quasar abundance at different redshifts has been used as a test for model reliability (e.g. Nusser & Silk 1993; Pogosyan & Starobinsky 1993).

Recently, damped Lya systems (DLAS) have been recognized as a promising way to trace the presence of high-redshift collapsed structures, thanks to the possibility of identifying them as protogalaxies and to their detectability at high \( z \) (see Wolfe 1993 for a comprehensive review). DLAS are seen as wide absorption features in quasar spectra. The associated absorbing systems have a neutral hydrogen column density \( \gtrsim 10^{20} \text{ cm}^{-2} \). The rather large abundance of DLAS makes it possible to compile reliable statistical samples (Lanzetta 1993; Lanzetta et al. 1995; Storrie-Lombardi et al. 1995). Once the parameters of the Friedmann background are specified, observations of DLAS can be turned into the value of the cosmological density parameter \( \Omega_y \) contributed by the neutral gas, which is associated with DLAS. It turns out that at \( z \sim 3 \) this quantity is comparable to the mass density of visible matter in nearby galaxies, thus suggesting that DLAS trace a population of galaxy progenitors.

Based on the APM QSO catalogue, Storrie-Lombardi et al. (1995) recently presented the most extended DLAS sample up-to-date, covering the range \( 2.8 < z < 4.4 \). In the following of this paper we will consider their highest redshift data as the most constraining ones and we will compare them with model predictions.

Several authors (Subramanian & Padmanabhan 1994; Mo & Miralda-Escudé 1994; Kauffmann & Charlot 1994; Ma & Bertschinger 1994) have recently claimed that the large value of \( \Omega_y \) observed at \( z \gtrsim 3 \) is incompatible with predictions of the Mixed (i.e. cold-hot) Dark Matter (MDM) model with spectral index \( n = 1 \) and \( \Omega_y \approx 0.3 \) contributed by one species of massive neutrinos and \( \Omega_b = 0.1 \) for the baryon fractional density (Klypin et al. 1993; Nolthenius, Klypin & Primack 1995). Klypin et al. (1995) reached substantially the same conclusions about this model, but emphasized two relevant points: (i) any theoretical prediction is very sensitive to the choice of the parameters of the model to obtain \( \Omega_y \) from a given power-spectrum; (ii) slightly lowering \( \Omega_y \) to 20–25% keeps MDM into a better agreement with DLAS data, independently of whether the hot component is given by one or two massive neutrino species (see also Primack et al. 1995).

A possible alternative, still in the framework of MDM, is to consider 'blue' (\( n > 1 \)) primordial spectra of density fluctuations. The advantage of these models is an anticipation of the epoch of structure formation due to the higher small-scale power. The choice of blue spectra is suggested by Cosmic Microwave Background anisotropies on scales larger than 1° (e.g. Devlin et al. 1994; Hancock et al. 1994; Bennett et al. 1994). Possible indications for blue spectra come from large bulk flows (Lauer & Postman 1994; see however Riess, Press & Kirshner 1994; Branchini & Plionis 1995) and large voids in the galaxy distribution (Piran et al. 1993). In recent years many authors have pointed out that suitable inflationary dynamics can easily originate blue spectra (Lyttle & Lyth 1993; Linde 1994; Mollerach, Matarrese & Lucchin 1994; Copeland et al. 1994), in particular in the framework of the so-called hybrid models. Recently Lucchin et al. (1995), using linear theory and N-body simulations, performed an extended analysis of the large-scale structure arising from blue MDM (BMDM) models: the most interesting advantage of these models is the increase of the galaxy formation redshift (taking \( \Omega_y = 0.3 \) one has for redshift of non-linearity on galactic scale \( z_{nl} \approx 1.9 \) if \( n = 1.2 \) and \( z_{nl} \approx 0.6 \) if \( n = 1 \)). In this work we will compare BMDM model predictions, for
different values of \( \Omega_c \) and \( n \) (for the sake of comparison we also consider the \( 0.9 \leq n < 1 \) tilted models), with the observed DLAS abundance.

2 THE METHOD

In order to connect our model predictions to DLAS observables, let us define \( \Omega_{coll}(z) \) as the fractional matter density within collapsed structures at redshift \( z \). Therefore

\[
\Omega_{coll}(z) = \frac{\Omega_c(z)}{\Omega_f(z)}
\]

where \( \Omega_c \) is the fractional baryon density (since \( h = 0.5 \) is assumed throughout the paper, we take \( \Omega_c = 0.05 \) according to standard primordial nucleosynthesis; see, e.g., Reeves 1994) and \( f_g \) is the fraction of the HI gas, which is involved in DLAS. Although the observed decrease of \( \Omega_c \) with redshift at \( z \lesssim 3.5 \) is considered as an indication of gas consumption into stars (e.g., Lanzetta et al. 1995), the actual value of \( f_g \) at the high redshift we are interested in is not clear. For these reasons we will show results based both on \( f_g = 0.5 \) and 1.

Taking \( h = 0.5 \) and an Einstein–de Sitter universe, the data at \( z = 4.25 \) from Storrie-Lombardi et al. (1995) turn into \( \Omega_{coll} = (8.8 \pm 2.0) \times 10^{-2} \) and \( (4.4 \pm 1.0) \times 10^{-2} \) for \( f_g = 0.5 \) and 1, respectively.

From the theoretical side, the Press & Schechter (1974) approach gives a recipe to compute the contribution to the cosmic density due to the matter within collapsed structures of mass \( M \) at redshift \( z \):

\[
\Omega_{coll}(M, z) = \text{erfc} \left( \frac{\delta_c}{\sqrt{2} \sigma_M(z)} \right).
\]

The above expression assumes Gaussian fluctuations and \( \delta_c \) is the linearly extrapolated density contrast for the collapse of a perturbation; \( \sigma_M \) is the r.m.s. fluctuation at the mass-scale \( M \), where \( M = (2\pi R^2)^{3/2} \rho \) for the Gaussian window that we will assume in the following.

As for the mass of the structures hosting DLAS, it has been argued that, since the high column density of the absorber is typical of large disks of luminous galaxies, DLAS should be located within massive structures of \( \sim 10^{12} \, M_\odot \). However, it is not clear at all whether the properties of present-day galaxies can be extrapolated to their high-redshift progenitors. Therefore, we prefer to leave open the possibility that DLAS are hosted within smaller structures. It is clear that, when a model is in trouble in accounting for the DLAS abundance if the hosting structure is a dwarf galaxy (\( M \sim 10^{10} \, M_\odot \)), it would certainly be ruled out if more massive protogalaxies are required.

Linear theory for the top-hat spherical collapse predicts \( \delta_c = 1.69 \). However, effects of non-linearity as well as asphericity of the collapse could cause significant deviations from this value. Klypin et al. (1995) estimated halo abundance at different redshifts from high mass resolution N-body simulations. They found a good agreement with the Press–Schechter expression for values as low as \( \delta_c = 1.3-1.4 \) (see also Efstathiou & Rees 1988). On the other hand, Ma & Bertschinger (1994) found that \( \delta_c \approx 1.7 \) is always required. In the following we will prefer to show results based on \( \delta_c = 1.5 \) but, due to the previous uncertainties, we will discuss also the effect of different choices for \( \delta_c \).

For the MDM transfer function we take the fit obtained by Pogosyan & Starobinsky (1995), which provides a continuous dependence on the fractional density \( \Omega_c \) contributed by one massive neutrino. As for the cold part of the transfer function, we use the Cold Dark Matter expression by Efstathiou, Bond & White (1992), with the shape parameter \( \Gamma = \Omega_c \sigma_8 \exp(-2f_\nu) \), according to the prescription of Peacock & Dodds (1994), to account for the baryonic component. We varied \( \Omega_c \) in the interval \( 0 \leq \Omega_c \leq 0.5 \). We as-
sum for the primordial (post inflationary) power-spectrum $P(k) \propto k^n$ with $0.9 \leq n \leq 1.4$. Each model is normalized to the 9-4 multipole component of the COBE DMR two-year data (Gölski et al. 1994).

3 DISCUSSION

The results of our analysis are summarized in Figure 1, where we plot $\Omega_c$ against $n$ at $z = 4.25$, as a function of $\Omega_c$ (left panel) and of $n$ (right panel), after assuming $\delta_c = 1.5$ and $M = 10^{11} M_\odot$. As for the $\Omega_c$ dependence, results are plotted for $n = 0.9 - 1.4$ going from lower to upper curves with steps of 0.1. In such a fashion, going from higher to lower curves, we plot results for $\Omega_c = 6 - 0.5$ with steps of 0.1. Upper and lower error bars show the effect of taking $M = 10^{10} M_\odot$ and $10^{12} M_\odot$, respectively. The horizontal solid line is the observational result with the corresponding uncertainties (dotted lines), which is obtained by converting the $\Omega_c$ value, as reported by Storrie-Lombardi et al. (1995) at $z = 4.25$, to $\Omega_c$ according to eq.(1) with $f_g = 1$.

Figure 2 shows in the $\Omega_c$ -- $n$ plane the models which reproduce the observed $\Omega_c$, taking $f_g = 1$ (left panel) and $f_g = 0.5$ (right panel). The heavy solid curve corresponds to $\delta_c = 1.5$ and $M = 10^{11} M_\odot$, with the lighter curves delimiting the observational uncertainties. Upper and lower dashed lines show the effect of varying $\delta_c$ to 1.3 and 1.7, respectively. Upper and lower dotted curves refer to $M = 10^{10}$ and $10^{12} M_\odot$, respectively.

It should be noted that realistic observational error bars should be larger than those reported by Storrie-Lombardi et al. (1995). In fact, they do not include systematic uncertainties, such as amplification bias due to DLAS gravitational lensing of QSOs (Bartelmann & Loeb 1995), whose effects are still to be fully understood.

The overall result that we get is that decreasing the hot component fraction $\Omega_c$ and/or increasing the primordial spectral index $n$ implies an earlier formation of cosmic structures. It is however clear that, even taking the observational results at face value with their small error bars, the rather poor knowledge of the parameters entering in the Press-Schechter prediction for $\Omega_c$ (i.e. $\delta_c$, $M$, and $f_g$) makes it difficult to put stringent constraints on $\Omega_c$ and $n$.

For instance, if one takes $1.3 \leq \delta_c \leq 1.5$, as suggested by several N-body simulations (e.g. Efstathiou & Rees 1988; Klypin et al. 1995) and analytical considerations on the Press-Schechter approach (e.g. Jain & Bertschinger 1994), $\Omega_c \approx 0.2$ and $n = 1$ would be allowed for $M \approx 10^{10} - 10^{11} M_\odot$, unless $f_g$ is sensibly below unity. On the other hand, blueing the spectrum to $n = 1.2$ increases the allowed hot fraction to $\Omega_c \gtrsim 0.4$, unless $\delta_c \approx 1.7$ or $M \approx 10^{12} M_\odot$ are taken. In order to more tightly constrain the models, a better understanding of galaxy formation through hydrodynamical simulations would be needed to clarify what DLAS actually are. This would provide more reliable values for $\delta_c$, $M$, and $f_g$. On the other hand, those models which fit the data at $z \approx 4$ need to be tested against present-day observables, such as pairwise galaxy velocity dispersions and abundance of galaxy groups and clusters, whose careful investigation requires resorting to N-body simulations. In any case, the effects obtained by bluing the primordial perturbation spectrum go in the direction of increasing the redshift of structure formation, thereby widening the range of allowed parameters within the Mixed Dark Matter scenario.

Acknowledgments

The Italian MURST is acknowledged for partial financial support. SB wishes to thank Joel Primack for useful discussions.

REFERENCES
