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Physics of Structure Formation in the Universe

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Abstract. In recent years, unprecedented progress in observational cosmology has revealed a great deal of information about the formation and evolution of structures in the universe. This, in turn, has raised many challenging issues for the theorists. In the thesis, we have addressed two such key issues, namely, (a) the formation of baryonic structures and (b) the nature of dark matter and dark energy and the limitations in determining their nature from observations. The main results from the thesis are: (i) The baryons in the intergalactic medium at redshifts $z \sim 2.5$ can be modelled (both analytically and semi-analytically) by accounting for the non-linearities in the density field through lognormal approximation. Our results agree with observations, and can be used for constraining parameters related to the baryons. (ii) A simple model based on baryon conservation, along with observational estimates of cosmic star formation rate, correctly predicts the abundance of damped Lyman-α systems in the universe. (iii) The redshift distribution of gamma ray bursts can, in principle, be used for studying the physical conditions of the universe before reionization epoch (which is otherwise a difficult task). (iv) It might be possible that the dark matter and dark energy arise from the same scalar field, provided the equation of state has a dependence on the length scale. The possibility of using the kinematical and geometrical measurements (such as supernova observations) for determining the nature and evolution of the dark energy is discussed.

Keywords : cosmology: theory – large-scale structure of Universe – intergalactic medium – quasars: absorption lines — early universe

1. Introduction

In recent years, our understanding of the universe has been driven by tremendous progress in observational cosmology which has revealed a great deal of information about the geometry, mass distribution and composition, and formation and evolution of structures of the universe. The high

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accuracies in the measurement of most of the cosmological parameters helped the theoretical cosmologists to develop the so called "standard model" of cosmology – a model which is consistent with all the observations. However, these observations, have also left the theoretical cosmologists with some challenging issues. For example, we do not have any laboratory evidence for about 95 per cent of the matter component in the universe. About one third of these is a non-relativistic pressure-less fluid which does not interact with radiation, while the rest two-third is a negative pressure component. Similarly, we still do not have satisfactory models which describe the physics of the formation of baryonic structures, like galaxies, in the universe. In this thesis, we have addressed two key issues in this field, namely, (i) the formation of baryonic structures (Sections 2–5) and (ii) the nature of dark matter and dark energy and the limitations in determining their nature from observations (Section 6). The analytical and semi-analytical models described in this thesis are found to match excellently with current observational data, and can be further compared with improved datasets expected in near future.

2. Analytical Modelling of the Neutral Hydrogen Distribution in the Universe

A significant fraction of baryons at $z \leq 5$ is found in the form of a diffuse ionised intergalactic medium (IGM), which is usually probed through the absorption spectra of distant QSOs. Most of the low neutral hydrogen column density absorption lines (commonly called 'Lyα' clouds) in a typical QSO spectrum are believed to be due to low-amplitude baryonic fluctuations in the IGM. In this section, we model the distribution of neutral hydrogen in the universe at redshifts 2–4 and compare with observations of QSO spectra. We use an approximation scheme for the non-linear baryonic mass density – the lognormal ansatz. This ansatz was used earlier by Bi & Davidsen (1997) to perform one-dimensional simulations of lines of sight and analyse the properties of absorption systems. We have taken a completely analytical approach, which allows us to explore a wide region of the parameter space for our model. We have also assumed that the gas in the IGM is in a state of photoionization equilibrium, with the temperature and density of the gas being related by a simple power-law (usually called the equation of state of the IGM). The analytical results have been compared with observations to constrain various cosmological and IGM parameters, whenever possible (Choudhury, Padmanabhan, & Srianand 2001).

The analytical predictions for the line-of-sight (LOS) correlation of the neutral hydrogen distribution is compared with observational data obtained from the absorption spectra of distant QSOs in Figure 1. We find that the effects on the LOS correlation owing to changes in cosmology and the slope of the equation of state of the IGM, γ are of the same order, which means that we cannot constrain both the parameters simultaneously. Our models also reproduce the observed column density distribution for neutral hydrogen, and the shape of the distribution depends on γ (see Figure 2). It is evident from the figure that one can rule out $\gamma > 1.6$ for $z \simeq 2.31$ using the column density distribution.

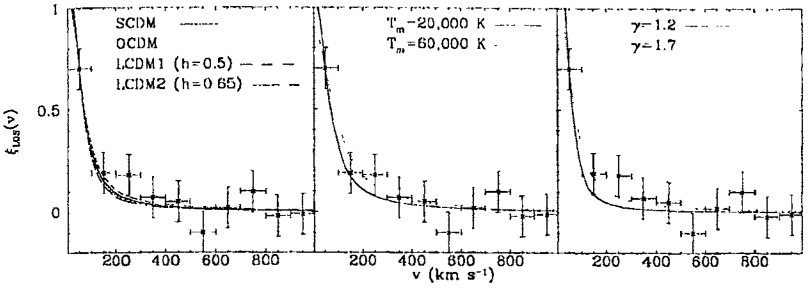

Figure 1. Comparison of the theoretical $\xi_{\rm LOS}$ with observational data (Cristiani et al. 1997). The theoretical curves have been normalized in such a way that they match with the observed data point at the lowest velocity bin. We show the dependence of the LOS correlation on background cosmological model (left), Jeans temperature T_m (centre) and slope of the equation of state γ (right). It is clear that one cannot constrain the background cosmological model without constraining the IGM parameters, especially γ.

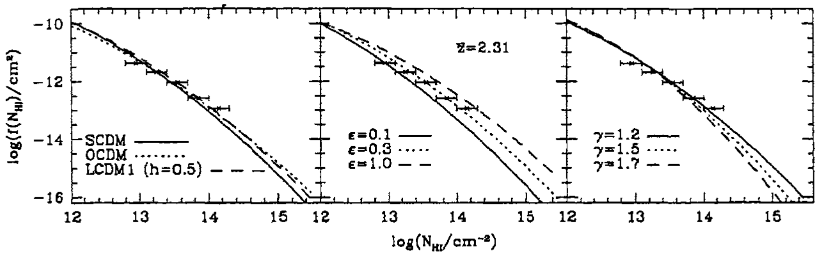

Figure 2. The column density distribution for neutral hydrogen $f(N_{\rm HI})$ for redshift 2.31. The data points with error-bars are obtained from Hu et al. (1995) and Kim et al. (1997) We show the dependence of $f(N_{\rm HI})$ on background cosmological model (left), parameter ϵ relating the column density to the density of the gas (centre) and slope of the equation of state γ (right).

3. Absorption Systems in the Universe: Comparison of Semi-analytical Model with Observations

We extend the analytical calculations of the previous section and perform one-dimensional semi-analytical simulations along the lines of sight to model the IGM. Since this procedure is computationally efficient in probing the parameter space – and reasonably accurate – we use it to recover the values of various parameters related to the IGM (for a fixed background cosmology) by comparing the model predictions with different observations (Choudhury, Srianand, & Padmanabhan

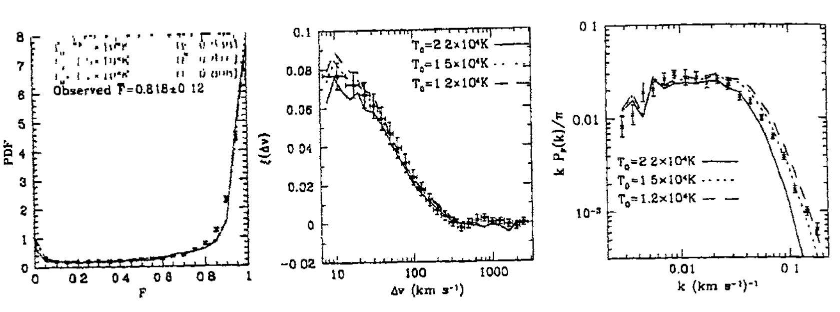

Figure 3. Comparison between simulations and observed results for $f \equiv (\Omega_B h^2)^2/J_{-12} = 0.026^2$, $\gamma = 1.5$ and three values of T_0 as indicated in the figure. The points with error-bars are the observed data points (McDonald et al. 2000). We have plotted the probability distribution function (left), the correlation function (middle) and the power spectrum (right) of the transmitted flux.

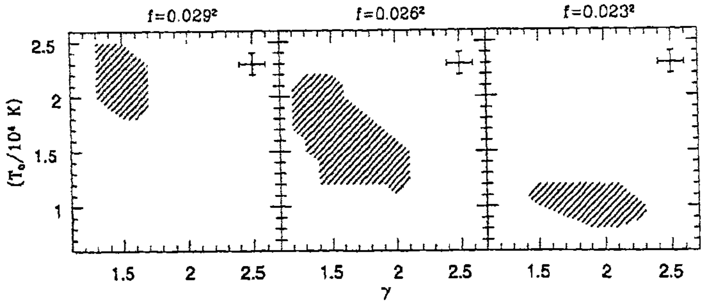

Figure 4. Constraints obtained in the $\gamma - T_0$ space for different values of f, *using transmitted flux statistics.* The shaded regions denote the range allowed by observations. The boundaries are uncertain by an amount 0.1 along γ axis and by 1000K along the T_0 axis because of finite sampling, which is shown by a cross at the upper right hand corners of the panels.

2001). For the Λ cold dark matter model ($\Omega_m = 0.4$, $\Omega_\Lambda = 0.6$ and $h = 0.65$), we find that the statistics obtained from the transmitted flux of the simulated absorption spectrum of QSOs match excellently with observations (see Figure 3) at a mean redshift $z \simeq 2.5$.

Further, using these transmitted flux statistics, we obtain constraints on (i) the combination $f = (\Omega_B h^2)^2/J_{-12}$, where Ω_B is the baryonic density parameter and J_{-12} is the total photoionization rate in units of $10^{-12}\mathrm{s}^{-1}$, (ii) temperature T_0 corresponding to the mean density, and (iii) the slope γ of the effective equation of state of the IGM. As an example, we show the constrained

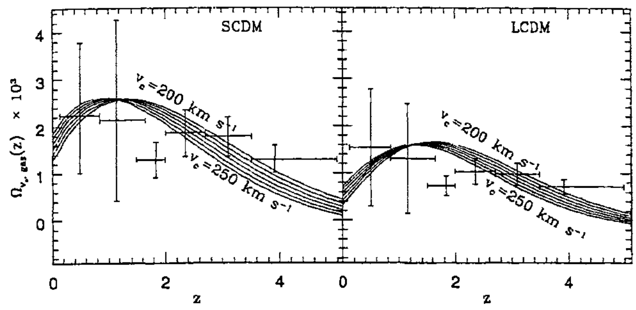

Figure 5. Density of matter contained in gaseous form $\Omega_{v_c,\text{gas}}(z)$ as a function of z, plotted for two cosmological models. The circular velocity ranges from $v_c = 200$ km s^{-1} to $v_c = 250$ km s^{-1} in both plots. The observed data points with error-bars are obtained from Peroux et al. (2001). As can be seen from the figure, the ballpark estimate of $\Omega_{v_c,\text{gas}}(z)$ from our simple model is well within observational constraints.

parameter space in the $\gamma - T_0$ plane for three values of f in Figure 4. It is obvious that as we go to lower values of f, the observations allow lower values of T_0 and higher values of γ. In general, we find that $0.8 < T_0/(10^4\text{K}) < 2.5$ and $1.3 < \gamma < 2.3$, while the constraint obtained on f is $0.020^2 < f < 0.032^2$. The bound on γ agrees with the usual models of reionization where the IGM becomes nearly isothermal ($\gamma \approx 1$) at the epoch of reionization and the value of γ increases afterwards. A reliable lower bound on J_{-12} can be used to put a lower bound on $\Omega_B h^2$, which can be compared with similar constraints obtained from big bang nucleosynthesis (BBN) and cosmic microwave background radiation (CMBR) studies.

4. Abundance of Damped Lyα Absorbers: A Simple Analytical Model

This section deals with comparatively high density regions, namely, the damped Lyα systems (DLAs). The DLAs are identified with the lines having highest column densities in a typical observed absorption spectrum of a distant quasar. These high column density systems are important in understanding the baryonic structure formation, because they contain a fair amount of the neutral hydrogen in the universe at high redshifts. As a preliminary study for understanding these systems, a simple analytical model for estimating the fraction (Ω_{gas}) of matter in gaseous form within the collapsed dark matter (DM) haloes is presented. The model is developed using (i) the Press-Schechter formalism to estimate the fraction of baryons in DM haloes and (ii) the observational estimates of the star formation rate at different redshifts. The prediction for Ω_{gas} from the model is in broad agreement with the observed abundance of the damped Lyα systems, which is shown in Figure 5. Furthermore, it can be used for estimating the circular velocities of the collapsed haloes at different redshifts, which could be compared with future observations (Choudhury & Padmanabhan 2002).

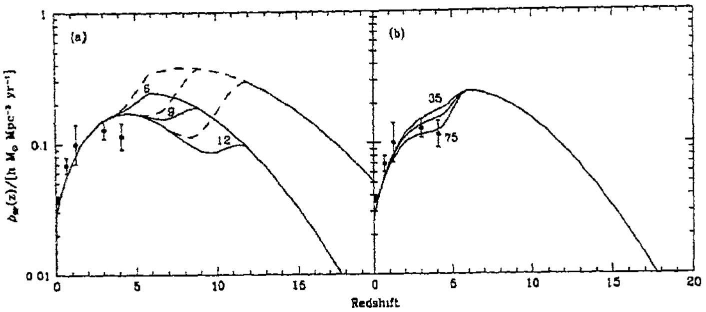

Figure 6. The SFR density as a function of redshift for three epochs of reionization and various model parameters [see Choudhury & Srianand (2002) for details]. The curves are normalized using the extinction corrected data points from Somerville, Primack, & Faber (2001).

5. Probing the Reionization Epoch with Redshift Distribution of Gamma-ray Bursts

In this section, we take our first step towards modelling the reionization. We explore the possibility of using the properties of gamma-ray bursts (GRBs) to probe the physical conditions in the epochs prior to reionization. The GRBs are among the brightest sources in the sky in any wavelength region. They are believed to originate due to collapse of very massive stars in the galaxies. In this section, the redshift distribution of GRBs is modelled using the Press-Schechter formalism with an assumption that they follow the cosmic star formation history. We reproduce the observed star formation rate (SFR) obtained from galaxies in the redshift range $0 < z < 5$ (Figure 6), as well as the redshift distribution of the GRBs inferred from the luminosity-variability correlation of the burst light curve (Choudhury & Srianand 2002). Interestingly, we find that the fraction of GRBs at high redshifts, the afterglows of which cannot be observed in R and I band owing to Hɪ Gunn-Peterson optical depth can, at the most, account for *one third of the dark GRBs*. This means that a substantial fraction of optically dark GRBs ($\gtrsim$ 66 per cent) originate because of effects such as dust extinction. The observed redshift distribution of GRBs, with much less scatter than the one available today, can put stringent constraints on the epoch of reionization and the nature of gas cooling in the epochs prior to reionization.

6. A Model for Dark Matter and Dark Energy

This section deals with issues related to the nature of dark matter and dark energy. Current cosmological observations strongly suggest the existence of two different kinds of energy densities dominating at small ($\lesssim$ 500 Mpc) and large ($\gtrsim$ 1000 Mpc) scales. The dark matter component, which dominates at small scales, contributes $\Omega_m \approx 0.35$ and has an equation of state $p = 0$, while

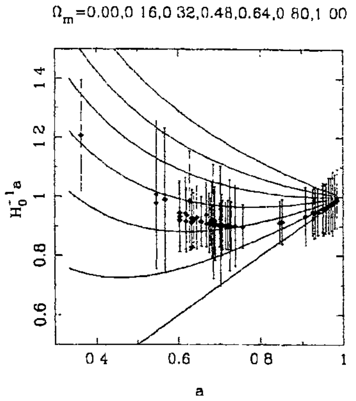

Figure 7. The observed supernova data points in the $\dot{a} - a$ plane for flat models, where a is the scale factor. The procedure for obtaining the data points and the corresponding error-bars are described in Padmanabhan & Choudhury (2003). The solid curves, from bottom to top, are for flat cosmological models with $\Omega_m = 0.00, 0.16, 0.32, 0.48, 0.64, 0.80, 1.00$ respectively.

the dark energy component, which dominates at large scales, contributes $\Omega_\Lambda \approx 0.65$ and has an equation of state $p \simeq -\rho$. The most obvious candidate for this dark energy is the cosmological constant (with the equation of state $w_X = p/\rho = -1$), which, however, raises several theoretical difficulties. This has led to models for dark energy component which evolves with time. We discuss certain questions related to the determination of the nature of dark energy component from observations of high redshift supernova. The main results of our analysis are:

(i) It is usual to postulate weakly interacting massive particles (WIMPs) for the dark matter component and some form of scalar field or cosmological constant for the dark energy component. We explore the possibility of a scalar field with a Lagrangian $L = -V(\phi)\sqrt{1 - \partial^i\phi\partial_i\phi}$ acting as *both* clustered dark matter and smoother dark energy and having a scale-dependent equation of state (Padmanabhan & Choudhury 2002). This model predicts a relation between the ratio $r = \rho_\Lambda/\rho_{\rm DM}$ of the energy densities of the two dark components and expansion rate n of the universe [with $a(t) \propto t^n$] in the form $n = (2/3)(1 + r)$. For $r \approx 2$, we get $n \approx 2$ which is consistent with supernova observations.

(ii) Although the full data set of supernova observations (which are currently available) strongly rule out models without dark energy, the high ($z > 0.25$) and low ($z < 0.25$) redshift data sets, individually, admit decelerating models with zero dark energy (see Figure 7). Any possible evolution in the absolute magnitude of the supernovae, if detected, might allow the decelerating models to be consistent with the data.

(iii) By studying the sensitivity of the luminosity distance on w_X, it is possible to argue that although one can determine the present value of w_X accurately from the data, one cannot constrain the evolution of w_X (Padmanabhan & Choudhury 2003).

7. Summary

The first part of the thesis is devoted to understanding the baryonic structure formation in the universe. We have developed various semi-analytical models to understand different aspects of the thermal history of baryons. The models, based on some reasonable approximations, are found to agree with current observations. In the next part of the thesis, we have addressed a more general issue of the nature of dark matter and dark energy in the universe. Our understanding of the subject is far from complete – the unresolved issues will be settled only through future observations. There is no doubt that computer simulations will play a major role in order to understand such observations – however the limitations due to computational power will always be a hurdle. Thus one needs to carry out calculations based on simple ideas and approximations so as to keep pace with progress in observational cosmology – like what is done in the thesis.

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