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INTERIM REPORT

The Universe at Moderate Redshift

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PROGRESS REPORT

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Progress Report

The work done in the past year by J.P. Ostriker, R. Cen, J.R. Gott and collaborators covered a wide range of fields including properties of clusters of galaxies, topological properties of galaxy distributions in terms of galaxy types, patterns of gravitational nonlinear clustering process, development of a ray tracing algorithm to study the gravitational lensing phenomenon by galaxies, clusters and large-scale structure, one of whose applications being the effects of weak gravitational lensing by large-scale structure on the determination of q_0, the origin of magnetic fields on the galactic and cluster scales, the topological properties of Lyα clouds the Lyα optical depth distribution, clustering properties of Lyα clouds, and a determination (lower bound) of Ω_b based on the observed Lyα forest flux distribution. In the coming year, we plan to continue the investigation of Lyα clouds using larger dynamic range (about a factor of two) and better simulations (with more input physics included) than what we have now. We will study the properties of galaxies on $1 - 100h^{-1}$Mpc scales using our state-of-the-art large scale galaxy formation simulations of various cosmological models, which will have a resolution about a factor of 5 (in each dimension) better than our current, best simulations. We will plan to study the properties of X-ray clusters using unprecedented, very high dynamic range (20,000) simulations which will enable us to resolve the cores of clusters while keeping the simulation volume sufficiently large to ensure a statistically fair sample of the objects of interest. The details of the last year's works are now described.

R. Cen, J.R. Gott and J.P. Ostriker have studied the topology of large scale structure as a function of galaxy type using the genus statistic. In hydrodynamical cosmological CDM simulations, galaxies form on caustic surfaces (Zeldovich pancakes) then slowly drain onto filaments and clusters. The earliest forming galaxies in the simulations (defined as "ellipticals") are thus seen at the present epoch preferentially in clusters (tending toward a meatball topology), while the latest forming galaxies (defined as "spirals") are seen currently in a spongelike topology. The topology is measured by the genus (= number of "donut" holes - number of isolated regions) of the smoothed density-contour surfaces. The measured genus curve for all galaxies as a function of density obeys approximately the theoretical curve expected for random-phase initial conditions, but the early forming elliptical galaxies show a shift toward a meatball topology relative to the late forming spirals. Simulations using standard biasing schemes fail to show such an effect. Large observational samples separated by galaxy type could be used to test for this effect.

R. Cen and J.P. Ostriker, with T.Padmanabhan (India) and F.J. Summers, have studied the nonlinear clustering of dark matter particles in an expanding universe using N-body simulations. One can gain some insight into this complex problem if simple relations between physical quantities in the linear and nonlinear regimes can be extracted from the results of N-body simulations. Hamilton et al. (1991) and Nityananda and Padmanabhan (1994) have made an attempt in this direction by relating the mean relative pair velocities to the mean correlation function in a useful manner. They investigate this relation and other closely related issues in detail for the case of six different power spectra: power laws with spectral indexes $n = -2, -1$, cold dark matter (CDM), and hot dark matter models with density parameter $\Omega = 1$; CDM including a cosmological constant (Λ) with $\Omega_{CDM} = 0.4$, $\Omega_\Lambda = 0.6$; and $n = -1$ model with $\Omega = 0.1$. They find that: (i) Power law spectra lead to self-similar evolution in an $\Omega = 1$ universe. (ii) Stable clustering does not hold in an $\Omega = 1$ universe to the extent our simulations can ascertain. (iii) Stable clustering is a better approximation in the case of $\Omega < 1$ universe in which structure formation freezes out at some low redshift. (iv) The relation between dimensionless pair velocity and the mean correlation function, $\bar{\xi}$, is only approximately independent of the shape of the power spectrum. At the nonlinear end, the asymptotic value of the dimensionless pair velocity decreases with increasing small scale power, because the stable clustering assumption is not universally true. (v) The relation between the evolved $\bar{\xi}$ and the linear regime $\bar{\xi}$ is also not universal but shows a weak spectrum dependence. They present simple theoretical arguments for these conclusions.

R. Cen and J.P. Ostriker, in collaboration with J. Wambsganss (MPE, Germany), have described in detail a new method to trace light rays through an essentially three dimensional mass distribution up to high redshift. As an example, we apply this method here to a standard cold dark matter universe. We obtain a variety of results, some of them statistical in nature, others from rather detailed case studies of individual "lines of sight". Among the former are the frequency of multiply imaged quasars, the distribution of separation of the multiple quasars, and the redshift distribution of lenses: all that as a function of quasar redshift. We find effects from very weak lensing up to highly magnified multiple images of high redshift objects. Applied to extended sources, i.e. galaxies, this ranges from slight deformations of the shapes, only measurable in a big ensemble, through tangentially aligned arclets up to giant luminous arcs. We can study the weak coherent shear fields produced by lensing of large scale structure in directions that are devoid of large mass concentrations as well as the strong lensing around massive clusters of galaxies. Gravitational lensing directly measures mass density fluctuations along the line of sight to very distant objects. No assumptions need to be made concerning bias, the ratio of fluctuations in galaxy density to mass density. Hence lensing is a good tool to study the universe at medium and high redshifts. Cosmological models – normalized to the universe at redshift zero – differ considerably in their predictions for the mass distributions at these distance scales. Therefore lensing is a powerful tool to distinguish between various cosmological models. Our ultimate goal is to apply this method to a number of cosmogonic models in order to study their gravitational lensing effects and be able to eliminate some models whose properties are very different from the properties of the observed universe.

R. Cen and J.P. Ostriker, in collaboration with J. Wambsganss (MPE, Germany) and G. Xu (Santa Cruz), have examined effects of the weak gravitational lensing by large-scale structure on the determination of the cosmological deceleration parameter q_0. They find that the lensing induced dispersions on truly standard candles are 0.04 and 0.02 mag at redshift $z = 1$ and $z = 0.5$, respectively, in a COBE-normalized cold dark matter universe with $\Omega_0 = 0.40$, $\Lambda_0 = 0.6$, $H = 65$km/s/Mpc and $\sigma_8 = 0.79$. It is shown that one would observe $q_0 = -0.44^{+0.17}_{-0.05}$ and $q_0 = -0.45^{+0.10}_{-0.03}$ (the errorbars are 2σ limits) with standard candles with zero intrinsic dispersion at redshift $z = 1$ and $z = 0.5$, respectively, compared to the truth of $q_0 = -0.40$ in this case, i.e., a 10% error in q_0 will be made. A standard COBE normalized $\Omega_0 = 1$ CDM model would produce three times as much variance and a mixed (hot and cold) dark matter model would lead to an intermediate result. One unique signature of this dispersion effect is its non Gaussianity. Although the lensing induced dispersion at lower redshift is still significantly smaller than the currently best observed (total) dispersion of 0.12 mag in a sample of type Ia supernovae, selected with the multicolor light curve shape method, it becomes significant at higher redshift. They show that there is an optimal redshift, in the range $z \sim 0.5 - 2.0$ depending on the amplitude of the intrinsic dispersion of the standard candles, at which q_0 can be most accurately determined.

R. Cen, with an undergraduate student R.A. Simcoe, performed a detailed analysis of the Lyα clouds produced by cosmological hydrodynamic simulations of a spatially flat cold dark matter universe with a non-zero cosmological constant. We find a very wide variety of structures, ranging from roundish high density regions with $N_{HI} > 10^{16}$ cm^{-2}, to filemantary and sheet-like structures with column densities below 10^{14} cm^{-2}. The most common shape of the Lyα clouds found in this simulation resembles a cigar squashed in the longitudinal direction. Furthermore, these Lyα clouds range in size from several kiloparsecs to about a hundred kiloparsecs, indicating that if simple models with a single population of uniformly sized spheres (or other shapes) fit observations, this is only by coincidence. We show that the method of inferring the sizes of Lyα clouds using observations of double quasar sightlines is only meaningful (in terms of setting lower limits on cloud sizes) when the sightline separations are small ($\Delta r < 50h^{-1}$kpc). Finally, we conjecture that high column density Lyα clouds ($N_{HI} > 10^{16}$cm^{-2}) may be progenitors of the lower redshift faint blue galaxies, because the correlation length of these Lyα clouds (extrapolated to lower redshift) resembles that of the observed faint blue galaxies, and their masses are close to those of starburst dwarf galaxies in the Babul & Rees proposal.

R. Cen and J.P. Ostriker, in collaboration with J. Miralda-Escude (U Penn) and M. Rauch (Caltech), used an Eulerian hydrodynamic cosmological simulation to model the Lyα forest in a spatially flat, COBE normalized, cold dark matter model with $\Omega = 0.4$. We find that the intergalactic, photoionized gas is predicted to collapse into sheet-like and filamentary structures which give rise to absorption lines having characteristics similar to the observed Lyα forest. A typical filament is $\sim 1h^{-1}$ Mpc long with thickness $\sim 50 - 100h^{-1}$ kpc (in proper units), and baryonic mass $\sim 10^{10}h^{-1} M_\odot$. In comparison our cell size is $(2.5, 9)h^{-1}$kpc in the two simulations we perform, with true resolution perhaps a factor of 2.5 worse than this. The gas temperature is in the range 10^4 - 10^5 K and it increases with time as structures with larger velocities collapse gravitationally.

We show that the predicted distributions of column densities, b-parameters and equivalent widths of the Lyα forest clouds agree reasonably with observations, and that their evolution is consistent with the observed evolution, if the ionizing background has an approximately constant intensity between $z = 2$ and $z = 4$. A new method of identifying lines as contiguous regions in the spectrum below a fixed flux threshold is suggested to analyze the absorption lines, given that the Lyα spectra arise from a continuous density field of neutral hydrogen rather than discrete clouds. We also predict the distribution of transmitted flux and its correlation along a spectrum and on parallel spectra, and the He II flux decrement as a function of redshift. We predict a correlation length of $\sim 80h^{-1}$ kpc perpendicular to the line of sight for features in the Lyα forest.

In order to reproduce the observed number of lines and average flux transmission, the baryon content of the clouds may need to be significantly higher than in previous models because of the low densities and large volume-filling factors we predict. If the background intensity $J_{H\,I}$ is at least that predicted from the observed quasars, Ω_b needs to be as high as $\sim 0.025h^{-2}$, higher than expected by light element nucleosynthesis; the model also predicts that most of the baryons at $z > 2$ are in Lyα clouds, and that the rate at which the baryons move to more overdense regions is slow. A large fraction of the baryons which are not observed at present in galaxies might be intergalactic gas in the currently collapsing structures, with $T \sim 10^5 - 10^6$ K.

J.P. Ostriker, with N.Y. Gnedin, we simulated a plausible cosmological model in considerable physical and numerical detail through the successive phases of reheating (at $10 < z < 20$), formation of Pop III stars at z=15 (due to molecular hydrogen cooling), with subsequent reionization at z=7. We assume an efficiency of high mass star formation appropriate to leave the universe, after it becomes transparent, with an ionizing background $J_2 1 = 0.4$ (at z=4), near (and perhaps slightly below) the observed value. Since the same stars produce the ionizing radiation and the first generation of heavy elements, a mean metallicity of $Z/Z_\odot = 1/200$ is produced in this early phase, but there is a large variation about this mean, with the high density regions having $Z/Z_\odot = 1/30$ and low density regions essentially no metals. Reionization, when it occurs, is very rapid, which will leave a signature which may be detectable by very large area meter-wavelength radio instruments. Also, the background UV radiation field will show a sharp drop from 1Ryd to 4Ryd due to absorption edges. The simulated volume is too small to form L_* galaxies, but the smaller objects which are found in the simulation obey the Faber-Jackson relation. In order to explore theoretically this domain of "the end of the dark ages" quantitatively, numerical simulations must have a mass resolution of the order of $10^{4.5} M_\odot$ in baryons, high spatial resolution (1 kpc) to resolve strong clumping, and allow for detailed and accurate treatment of both the radiation field and atomic/molecular physics.

R. Cen and J.P. Ostriker, in collaboration with R. Kulsrud and D. Ryu, demonstrated that strong magnetic fields are produced from a zero initial magnetic field during the pregalactic era, when the galaxy is first forming. Their development proceeds in three phases. In the first phase, weak magnetic fields are created by the Biermann battery mechanism. During the second phase results from a numerical simulation make it appear likely that homogenous isotropic Kolmogoroff turbulence develops associated with gravitational structure formation of galaxies. Assuming that this turbulence is real then these weak magnetic fields will be amplified to strong magnetic fields by this Kolmogoroff turbulence. During this second phase, the magnetic fields reach saturation with the turbulent power, but they are coherent only on the scale of the smallest eddy. During the third phase, which follows this saturation, it is expected that the magnetic field strength will increase to equipartition with the turbulent energy and the coherence length of the magnetic fields will increase to the scale of the largest turbulent eddy, comparable to the scale of the entire galaxy. The resulting magnetic field represents a galactic magnetic field of primordial origin. No further dynamo action after the galaxy forms is necessary to explain the origin of magnetic fields. However, the magnetic field will certainly be altered by dynamo action once the galaxy and the galactic disk have formed.

It is first shown by direct numerical simulations that thermoelectric currents associated with the Biermann battery build the field up from zero to 10^{-21} G in the regions about to collapse into galaxies. by $z \sim 3$. For weak fields in the absence of dissipation the cyclotron frequency $\omega_{\mathbf{cyc}} = e\mathbf{B}/m_H c$ and $\omega/(1+\chi)$ where $\omega = \nabla \times \mathbf{v}$ is the vorticity, and χ is the degree of ionization, satisfy the same equations, and initial conditions $\omega_{\mathbf{cyc}} = \omega = 0$, so that, globally $\omega_{\mathbf{cyc}}(\mathbf{r}, t) = \omega(\mathbf{r}, t)/(1+\chi)$. The vorticity grows rapidly after caustics (extreme nonlinearities) develop in the cosmic fluid. At this time it is made plausible that turbulence has developed into Kolmogoroff turbulence. Numerical simulations do not yet have the resolution to demonstrate that, during the second phase, the magnetic fields are amplified by the dynamo action of the turbulence. Instead, an analytic theory of the turbulent amplification of magnetic fields is employed to explore this phase of the magnetic field development. From this theory it is shown that, assuming the turbulence is really Kolmogoroff turbulence, the dynamo action of this protogalactic turbulence is able to amplify the magnetic fields by such a large factor during the collapse of the protogalaxy that the power into the magnetic field must reach saturation with the turbulent power. For the third phase there is as yet no analytic theory capable of describing the third phase. However, preliminary turbulence calculations currently in progress seem to confirm that the magnetic fields may proceed to equipartition with the turbulent energy, and that the coherence length may increase to the largest scales. simple physical arguments are presented that this may be the case. Such an equipartition field is actually too strong to allow immediate collapse to a disk. Possible ways around this difficulty are discussed.

R. Cen studied the projection effects on various observables of clusters of galaxies at redshift near zero, including cluster richness, velocity dispersion, X-ray luminosity, three total mass estimates (velocity-based, temperature-based and gravitational lensing derived), gas fraction and substructure, utilizing a large simulation of a realistic cosmological model (a cold dark matter model with the following parameters: $H_0 = 65$km/s/Mpc, $\Omega_0 = 0.4$, $\Lambda_0 = 0.6$, $\sigma_8 = 0.79$). Unlike previous studies focusing on the Abell clusters, we conservatively assume that both optical and X-ray observations can determine the source (galaxy or hot X-ray gas) positions along the line of sight as well as in the sky plane accurately; hence we only include sources inside the velocity space defined by the cluster galaxies (filtered through the pessimistic 3σ clipping algorithm) as possible contamination sources. Projection effects are found to be important for some quantities but insignificant for others.

It was shown that, on average, the gas to total mass ratio in clusters appears to be 30-40% higher than its corresponding global ratio. Independent of its mean value, the broadness of the observed distribution of gas to total mass ratio is adequately accounted for by projection effects, alleviating the need to invoke (though not preventing) other non gravitational physical processes. While the moderate boost in the ratio narrows the gap, it is still not quite sufficient to reconcile the standard nucleosynthesis value of $\Omega_b = 0.0125(H_0/100)^{-2}$ (Walker et al. 1991) and $\Omega_0 = 1$ with the observed gas to mass ratio value in clusters of galaxies, $0.05(H_0/100)^{-3/2}$, for any plausible value of H_0. However, it is worth noting that real observations of X-ray clusters, especially X-ray imaging observations, may be subject to more projection contaminations than we allow for in our analysis. In contrast, the X-ray luminosity of a cluster within a radius $\leq 1.0h^{-1}$Mpc is hardly altered by projection, rendering the cluster X-ray luminosity function a very useful and simple diagnostic for comparing observations with theoretical predictions.

Rich cluster masses $[M(< 1.0h^{-1}Mpc) \geq 3\times 10^{14}h^{-1}\,M_\odot]$ derived from X-ray temperatures or galaxy velocity dispersions underestimate, on average, the true cluster masses by about 20%, with the former displaying a smaller scatter, thus providing a better means for cluster mass determination. The gravitational lensing reconstructed (assuming an ideal inversion) mass is, on average, overestimates the true mass by only 5-10% but displays a dispersion significantly larger than that of the X-ray determined mass. The ratio of the lensing derived mass to the velocity or temperature derived mass is about 1.2-1.3 for rich clusters, with a small fraction reaching about $\sim$ 2.0. The dispersion in that ratio increases rapidly for poor clusters, reaching about 1.0-2.0 for clusters with masses of $M \sim 1-3\times 10^{14}\,M_\odot$. It appears that projection effects alone may be able to account for the disparities in existing observational data for cluster masses, determined by various methods.

Projection inflates substructure measurements in galaxy maps, but affects X-ray maps much less. Most clusters ($\geq 90\%$) in this model universe do not contain significant intrinsic substructure on scales $\geq 50h^{-1}$kpc at $R_{proj} \leq 1h^{-1}$Mpc without projection effects, whereas more than $\sim 50\%$ of the same clusters would be "observed" to show statistically significant substructure as measured by the Dressler-Shectman Δ statistic. The fact that a comparable fraction ($\sim 50\%$) of real observed clusters show substructure measured in the same way implies that most of the substructure observed in real clusters of galaxies may be due to projection.

Finally, we point out that it is often very difficult to correctly interpret complex structures seen in galaxy and X-ray maps of clusters, which frequently display illusory configurations due to projection. Until we can determine real distances of X-ray sources and galaxies accurately, for some observables, the only meaningful way to compare predictions of a cosmological model with the cluster observations is to subject clusters in a simulated universe to exactly the same observational biases and uncertainties, including projection and other instrumental limitations, and to compare the "observed" simulated clusters with real ones.

R. Cen investigated the high end of the Lyα optical depth distribution of a quasar spectrum. Based on the flux distribution (Miralda-Escudé et al. 1996), a simple yet seemingly cosmological model-differentiating statistic, Δ_{τ_0} — the cumulative probability of a quasar spectrum with Lyα optical depth greater than a high value τ_0 — is emphasized. It is shown that two different models — the cold dark matter model with a cosmological constant and the mixed hot and cold dark matter model, both normalized to COBE and local galaxy cluster abundance — yield quite different values of Δ_{τ_0}: 0.13 of the former versus 0.058 of the latter for $\tau_0 = 3.0$ at $z = 3$. Moreover, it is argued that Δ_{τ_0} may be fairly robust to compute theoretically because it does not seem to depend sensitively on small variations of simulations parameters such as radiation field, cooling, feedback process, radiative transfer, resolution and simulation volume within the plausible ranges of the concerned quantities. Furthermore, it is illustrated that Δ_{τ_0} can be obtained sufficiently accurately from currently available observed quasar spectra for $\tau_0 \sim 3.0 - 4.0$, when observational noise is properly taken into account. We anticipate that analyses of observations of quasar Lyα absorption spectra over a range of redshift may be able to constrain the redshift evolution of the amplitude of the density fluctuations on small-to-intermediate scales, therefore providing an independent constraint on Ω_0, $\Omega_{0,HDM}$ and Λ_0.

R. Cen studies the cluster-cluster two-point correlation functions in topological defect models. Gaussian cosmological models, typified by the inflationary cold dark matter models, and non-Gaussian topological defect based cosmological models, such as the texture seeded model, differ in the origin of large-scale cosmic structures. In the former it is believed that peaks at appropriate scales in the initial high density field are the sites onto which matter accretes and collapses to form the present galaxies and clusters of galaxies, whereas in the latter these structures can form around the density perturbation seeds (which are textures in the texture model). Textures initially are randomly distributed on scales larger than their size, in sharp contrast to the initial high density peaks in the Gaussian models which are already strongly clustered before any gravitational evolution has occured. One thus expects that the resultant correlation of large cosmic objects such as clusters of galaxies in the texture model should be significantly weaker than its Gaussian counterpart.

It was shown that an $\Omega_0 = 1$ biased $b = 2$ (as required by cluster abundance observations) texture model (or any random seed model) predicts a two-point correlation length of $\leq 6.0h^{-1}$Mpc for rich clusters, independent of richness. On the other hand, the observed correlation length for rich clusters is $\geq 10.0h^{-1}$Mpc at an approximately 2σ confidence level. It thus appears that the global texture cosmological model or any random seed cosmological models are ruled out at a very high confidence ($> 3\sigma$).

R. Cen and J.P. Ostriker, with a Princeton physics graduate student S. Phelps and J. Miralda-Escudé (U Penn), examined the correlational property of Lyα clouds (along the line of sight) in detail utilizing a hydrodynamic simulation of Lyα clouds in a cold dark matter universe with a cosmological constant, and compare it to that of mass and galaxies. We show that the correlation strength of Lyα clouds is somewhat weaker than that of the underlying matter, which in turn should be weaker than that of galaxies (biased galaxy formation). On the scales probed, 10−300km/s, for Lyα clouds we find that higher density, higher optical depth, higher column density regions are more strongly clustered than lower density, lower optical depth, lower column density regions, with the difference being larger at small separations and smaller at large separations. Thus, a consistent picture seems to emerge: the correlation strength for a given set of objects is positively correlated with their characteristic global density and the differences among the correlations of galaxies, Lyα clouds and mass reflect the differences in density that each trace. Significant positive correlations with a strength of 0.1 − 1.0 are found for Lyα clouds in the velocity range 50 − 300km/s. This effect should be observable. The correlation function of Lyα clouds seems to be a monotonically decreasing function of separation, indicating that correlation strength should be less than 0.1 at $\Delta v > 300$km/s, where our current simulation box is too small to give a reliable measure.

Among the correlational measures examined, an optical depth correlation function (Equation 5) proposed here may serve as the best correlational measure. It reasonably faithfully represents the true correlation of the underlying matter, enabling a better indication of both matter correlation and the relationship between galaxies and Lyα clouds. Furthermore, it appears to be an alternative to the conventional line-line correlation function with the virtue that it does not require ambiguous post-observation fitting procedures such as those commonly employed in the conventional line-finding methods. Neither does it depend sensitively on the observational resolution (e.g., FWHM), insofaras the clouds are resolved (i.e., the FWHM is smaller than the line width). Conveniently, it can be easily measured with the current observational sensitivity without being contaminated significantly by the presence of noise, if one chooses an appropriate optical depth floor value τ_{min} (an adjustable parameter) say, ≤ 2.0.

R. Cen, in collaboration with N. A. Bahcall and. X.Fan, shows that the evolution of the number density of rich clusters of galaxies breaks the degeneracy between Ω (the mass density ratio of the universe) and σ_8 (the normalization of the power spectrum), $\sigma_8\,\Omega^{0.5} \simeq 0.5$, that follows from the observed present-day abundance of rich clusters. The evolution of high-mass (Coma-like) clusters is strong in $\Omega = 1$, low-σ_8 models (such as the standard biased CDM model with $\sigma_8 \simeq 0.5$), where the number density of clusters decreases by a factor of $\sim 10^3$ from $z = 0$ to $z \simeq 0.5$; the same clusters show only mild evolution in low-Ω, high-σ_8 models, where the decrease is a factor of ~ 10. This diagnostic provides a most powerful constraint on Ω. Using observations of clusters to $z \simeq 0.5 - 1$, we find only mild evolution in the observed cluster abundance. We find $\Omega = 0.3 \pm 0.1$ and $\sigma_8 = 0.85 \pm 0.15$ (for $\Lambda = 0$ models; for $\Omega + \Lambda = 1$ models, $\Omega = 0.34 \pm 0.13$). These results imply, if confirmed by future surveys, that we live in a low-density, low-bias universe.

R. Cen, in collaboration with N. A. Bahcall and. X.Fan, presents a method for determining the rms mass fluctuations on 8 h^{-1}Mpc scale, σ_8. The method utilizes the rate of evolution of the abundance of rich clusters of galaxies. Using the Press-Schechter approximation, we show that the cluster abundance evolution is a strong function of σ_8: $d\log n/dz \propto -1/\sigma_8^2$; low σ_8 models evolve exponentially faster than high σ_8 models, for a given mass cluster. For example, the number density of Coma-like clusters decreases by a factor of $\sim 10^3$ from $z = 0$ to $z \simeq 0.5$ for σ_8=0.5 models, while the decrease is only a factor of ~ 5 for $\sigma_8 \simeq 1$. The strong exponential dependence on σ_8 arises because clusters represent rarer density peaks in low σ_8 models. We show that the evolution rate at $z \leq 1$ is relatively insensitive to the density parameter Ω or to the exact shape of the power spectrum. Cluster evolution therefore provides a powerful constraint on σ_8. Using available cluster data to $z \sim 0.8$, we find $\sigma_8 = 0.85 \pm 0.15$. This amplitude implies a bias parameter $b \simeq \sigma_8^{-1} = 1.2 \pm 0.2$, i.e., a nearly unbiased universe with mass approximately tracing light on large scales.

R. Cen and J.P. Ostriker, in collaboration with M. Rauch, J. Miralda-Escudé, W.L.W. Sargent, T.A. Barlow, D.H. Weinberg, L. Hernquist and N. Katz, have measured the distribution function of the flux decrement $D = e^{-\tau}$ caused by Lyα forest absorption from intervening gas in the lines of sight to high redshift QSOs from a sample of seven high resolution QSO spectra obtained with the Keck telescope. The observed flux decrement distribution function (FDDF) is compared to the FDDF from two simulations of the Lyα forest: a ΛCDM model (with Ω =0.4, Λ=0.6) computed with the Eulerian code of Cen & Ostriker, and a standard CDM model (SCDM, with $\Omega = 1$) computed with the SPH code of Hernquist, Katz, & Weinberg. Good agreement is obtained between the shapes of the simulated and observed FDDFs for both simulations after fitting only one free parameter, which controls the mean flux decrement. The difference between the predicted FDDFs from the two simulations is small, and we show that it arises mostly from a different temperature in the low-density gas (caused by different assumptions that were made about the reionization history in the two simulations), rather than differences between the two cosmological models *per se*, or numerical effects in the two codes which use very different computational methods.

A measurement of the parameter $\mu \propto \Omega_b^2 h^3/\Gamma$ (where Γ is the HI ionization rate due to the ionizing background) is obtained by requiring the mean flux decrement in the simulations to agree with the observed one. Estimating the lower limit $\Gamma > 7 \times 10^{-13}$ s^{-1} from the abundance of known QSOs, we derive a lower limit on the baryonic matter density, $\Omega_b h^2 > 0.021(0.017)$ for the ΛCDM (SCDM) model. The difference between the lower limit inferred from the two models is again due to different temperatures in the low-density gas. We give general analytical arguments for why this lower limit is unlikely to be reduced for any other models of structure formation by gravitational collapse that can explain the observed Lyα forest. The large Ω_b we infer is inconsistent with some recent D/H determinations (Rugers & Hogan 1996a,b), favoring a low deuterium abundance as reported by Tytler, Fan & Burles (1996). Adopting a fixed Ω_b, the measurement of $\mu(z)$ allows a determination of the evolution of the ionizing radiation field with redshift. Our models predict an intensity that is approximately constant with redshift, which is in agreement with the assumption that the ionizing background is produced by known quasars for $z < 3$, but requires additional sources of ionizing photons at higher redshift given the observed rapid decline of the quasar abundance.

J.P. Ostriker, with N.Y. Gnedin, noted that current observational evidence strongly favors a conventional recombination of ionized matter subsequent to redshift z=1200, followed by reionization prior to redshift z=5 and compute how this would have occurred in a standard scenario for the growth of structure. Extending prior semi-analytic work, we show by direct, high-resolution numerical simulations (of a COBE normalized CDM+Lambda model) that reheating, will occur in the interval $15 > z > 7$, followed by reionization and accompanied by a significant increase in the Jeans mass. However, the evolution of the Jeans mass does not significantly affect star formation in dense, self-shielded clumps of gas, which are detached from the thermal evolution of the rest of the universe. On average, the growth of the Jeans mass tracks the growth of the nonlinear mass scale, a result we suspect is due to nonlinear feedback effects. Cooling on molecular hydrogen leads to a burst of star formation prior to reheating which produces Population III stars with Ω_* reaching $10^{-5.5}$ and $Z/Z_\odot$ reaching $10^{-3.7}$ by z=14. Star formation subsequently slows down as molecular hydrogen is depleted by photo-destruction and the rise of the temperature. At later times, $z < 10$, when the characteristic virial temperature of gas clumps reach 10,000 degrees, star formation increases again as hydrogen line cooling become efficient. Objects containing Pop III stars accrete mass with time and, as soon as they reach 10,000 K virial temperature, they engage in renewed star formation and turn into normal Pop II objects having an old Pop III metal poor component.

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Papers Published

1. "Topology of Large-scale Structure by Galaxy Type: Hydrodynamic Simulations"
   J.R. Gott, R. Cen and J.P. Ostriker (1996)
   Astrophysical Journal, 465, 499
2. "Patterns in Nonlinear Gravitational Clustering: A Numerical Investigation"
   T. Padmanabhan, R. Cen, J.P. Ostriker, and F J Summers (1996)
   Astrophysical Journal, 466, 604
3. "The Lyman Alpha Forest from Gravitational Collapse in the CDM+Lambda Model"
   J. Miralda-Escude, R. Cen, J.P. Ostriker and M. Rauch (1996)
   Astrophysical Journal, 471, 582
4. "Reheating of the Universe and Population III"
   J.P. Ostriker and N.Y. Gnedin (1996)
   Astrophysical Journal, 471, L63
5. "Effects of Weak Gravitational Lensing from Large-Scale Structure of the Determination of q_0"
   Wambsganss, J., R. Cen, J.P. Ostriker and G. Xu (1997).
   Astrophysical Journal, 475, L81
6. "Testing Cosmological Models with a Lyman Alpha Cloud Statistic: The Fraction of a Quasar Spectrum with High Lyman Alpha Optical Depth"

R. Cen (1996)

Astrophysical Journal Letters, 479, L85

7. "The Protogalactic Origin For Cosmic Magnetic Fields"

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