Cosmology and Large Scale Structures
Contents

1 Topics ................................................. 1101

2 Participants ......................................... 1103
   2.1 Participants from University of Arizona .......... 1103
   2.2 Collaborators ................................... 1103
   2.3 Students ....................................... 1103

3 Brief description ...................................... 1105
   3.1 Cosmological hydrodynamics ....................... 1105
      3.1.1 WENO method ................................ 1105
      3.1.2 Statistical decoupling between IGM and dark matter 1107
      3.1.3 Multiple phase of IGM thermal state .......... 1108
   3.2 Turbulence-like behavior of cosmic baryon fluid 1109
      3.2.1 The IGM as a Burgers’ fluids ................. 1109
      3.2.2 Intermittence of cosmic baryon fluid ......... 1109
      3.2.3 Observable effects of turbulence-like behavior of cosmic baryon fluid 1110
   3.3 Physics of reionization epoch ..................... 1111
      3.3.1 The growth of ionized and heated regions .... 1111
      3.3.2 Absorption spectra of quasars at redshift $z > 5$ 1112
      3.3.3 21 cm signal from early universe ............. 1113


Bibliography ........................................... 1127
1 Topics

• The turbulence-like behavior of cosmic baryon fluid
  – Cosmological hydrodynamic simulation
  – Scaling and intermittence of IGM
  – Multiple phase of IGM thermal state.
  – Statistical decoupling between IGM and dark matter

• Physics of the epoch of reionization
  – Algorithm of radiative transfer and kinetics of photons
  – The increase of ionized and heated regions
  – Cosmology with high redshift quasar’s absorption spectrum
  – 21 cm emission from early universe

• Dissipation and fluctuation during Inflation (most works of this topic have been done before 2005).
2 Participants

2.1 Participants from University of Arizona
- Li-Zhi Fang
- Ji-Ren Liu

2.2 Collaborators
- Hong-Guan Bi (Purple mountain Observatory, Nanjing, PRChina)
- Yao-Quan Chu (University of Science and Technology of China, China)
- Long-long Feng (Purple mountain Observatory, Nanjing, China)
- Ping He (Institute of Theoretical Physics, Academia Sinica, Beijing)
- Jesus Pando (DePaul University, USA)
- Chu-Wang Shu (Brown University, USA)
- Tong-Jie Zhang (Beijing Normal University)
- Wei Zheng (John Hopkins University, USA)

2.3 Students
- Liang Cao (University of Arizona, USA)
- Jian-Mai Qiu (Brown University, USA)
- Priya Jamkhedkar (University of Arizona, USA)
2 Participants
3 Brief description

3.1 Cosmological hydrodynamics

3.1.1 WENO method

Though the universe seems to be dominated by the dark sides of both matter and energy (87), the observed luminous universe has been existing in the form of baryonic matter, whose mass density, constrained by the primordial nucleosynthesis (89), only occupies a small amount of the total density. To account for the observational features revealed by the baryonic matter, i.e., X-ray emitting gas in galaxies and clusters (56), intergalactic medium inferred from Ly$\alpha$ forest (69), X-ray background radiation (28) and distorted spectrum of the cosmic background radiation due to the Sunyaev-Zeldovich effect (94; 60), it would be necessary to incorporate the hydrodynamics into cosmological investigations. This motivation has stimulated great efforts to apply a variety of gas dynamics algorithms to cosmological simulations. For a general review of the state-of-the-art on this topic in non-relativistic and relativistic cases, we refer to, e.g. (4; 26; 51).

Although more than 10 cosmological hydrodynamical simulation codes have been proposed, there is still a need to develop codes based on new algorithms, with the objective of trying to obtain better performance for certain specific cosmological applications (it is probably impossible to have a code which performs better than others in all cosmological applications). In 1999, 11 codes were compared for their cluster simulation (25). The conclusion is that for thermal properties of clusters, such as entropy, X-ray luminosity etc., the results given by different codes are largely scattered. Therefore, new codes have been continuously proposed in recent years, e.g. (82; 83). The difficulty of the cosmological hydrodynamical simulation is due to the high non-linearity of gravitational Cosmological hydrodynamic flow poses more challenges than the typical hydrodynamic simulation without self-gravity. A significant feature is the extremely supersonic motion around the density peaks developed by gravitational instability, which leads to strong shock discontinuities within complex smooth structures. It would therefore be advantageous for the high order WENO schemes to be applied here, due to their capability to resolve both strong shocks and complicated smooth flow structures accurately at the same time. Qualified cosmological hydrodynamical simulation code should probably be able to pass two basic tests: 1. the
3 Brief description

Sedov-Taylor similarity solution or Bertschinger’s similarity solution; and 2. the Zeldovich pancake solution. The results of these two tests for 13 codes are listed in the table below:

<table>
<thead>
<tr>
<th>method</th>
<th>Sedov Blast wave</th>
<th>Zeldovich pancake</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bryan (7)</td>
<td>N/A</td>
<td>pass</td>
</tr>
<tr>
<td>2. Cen (Ryu) (73)</td>
<td>N/A</td>
<td>pass</td>
</tr>
<tr>
<td>3. Couchman (18)</td>
<td>fail</td>
<td>N/A</td>
</tr>
<tr>
<td>4. Evrard (21)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>5. Gnedin (29)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>6. Jenkins (63)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7. Navarro (58)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>8. Owen (61)</td>
<td>pass</td>
<td>N/A</td>
</tr>
<tr>
<td>9. Pen (64)</td>
<td>pass</td>
<td>pass</td>
</tr>
<tr>
<td>10. Steinmetz (80)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>11. Warren (90)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>12. Springel (83)</td>
<td>pass</td>
<td>N/A</td>
</tr>
<tr>
<td>13. WENO</td>
<td>pass</td>
<td>pass</td>
</tr>
</tbody>
</table>

where “pass” or “fail” refers to the result when the relevant test has been performed and reported, and “N/A” refers to the situation where there is no report on whether the test has been performed.

Among the listed codes, the Lagrangian approach generally is based on the smoothed particle hydrodynamic (SPH) algorithm. A main challenge to the smoothed particle hydrodynamic (SPH) algorithm is the handling of shocks or discontinuities, because the nature of SPH is to smooth the fields considered (6, 59). For the Eulerian approach in numerical cosmology, the better codes are based on the high resolution shock capturing total-variation diminishing (TVD) scheme (Harten (34)) and piecewise parabolic method (PPM) (Collella and Woodward (16)). Both schemes start from the integral form of conservation laws of Euler equations and compute the flux vector based on cell averages (finite volume scheme). The TVD scheme modifies the flux using an approximate solution of the Riemann problem with corrections added to ensure that there are no postshock oscillations. While in the PPM scheme, the Riemann problem is solved accurately using a quadratic interpolation of the cell-average densities that is constrained to minimize postshock oscillations.

Recently, we have performed quantitative study of applying high order WENO schemes for solving physical problems governed by high Reynolds number Navier-Stokes equations (79, 97), and have obtained the conclusion that high order WENO schemes are more CPU time efficient in achieving the same level of accuracy or resolution than lower order schemes for problems containing both strong shocks and complicated smooth flow structures. This indicates that the WENO scheme has the potential to present a significant improvement on the cosmological hydrodynamical simulation, especially in
3.1 Cosmological hydrodynamics

Figure 3.1: An $1^\circ \times 1^\circ$ map of X-ray intensity in soft-band 0.5-2 keV produced by WENO hydrodynamic simulation.

considering the accuracy and better efficiency in the application of cosmological problems. Moreover, the WENO scheme is also effective to deal with the radiative transfer, with equations similar to the Boltzmann-Poisson models in semiconductor device simulations that we have successfully simulated using the WENO scheme for both the one dimensional (one space dimension, two phase dimension plus time) and two dimensional (two space dimension, three phase dimension plus time) situations [8; 9; 10]. The WENO code developed in these references perform significantly better than other deterministic Boltzmann-Poisson solvers and produce results agreeing well with Monte-Carlo simulations. An eventual development of a WENO code for radiative transfer would be very beneficial for the study of the early universe. A preliminary application of WENO schemes for cosmological hydrodynamics has also been performed in Feng, Shu and Zhang [24].

3.1.2 Statistical decoupling between IGM and dark matter

In the linear regime, the mass and velocity fields of the IGM can be found by a similar mapping of the dark matter fields. However, observations have indicated that similarity between the IGM and dark matter is broken at the non-linear regime. A. X-ray measurements revealed that the baryon fraction in galaxy clusters is less than what the primordial nucleosynthesis predicts, and there is an increase in the volume-averaged baryon fraction with radii $r$ [20]. This implies that the mass fields of baryons is different from the dark matter fields on the scales of clusters. B. The high entropy floor observed in nearby groups and low mass clusters [65; 48] shows that there are hydro or radiative processes in the IGM that violate the dynamical similarity between dark matter and gas. Many models on the violation of the similarity have been proposed, such as photo-ionization heating [19; 30], SN explosions,
and AGN activities (81), gravitational shocks associated with clusters (11) or warm-hot gas (88). However, this problem is still open as recently shown, for instance, that the entropy excess over the whole cluster ranges (66). As this processes are highly nonlinear, the violation of the similarity should be studied with a detail cosmological hydrodynamical simulation. That is, it is necessary to simulate how the nonlinear evolution leads to the decoupling of the IGM from the underlying dark matter. This result would also be helpful in understanding the bias of galaxy distribution with respect to the dark matter.

A related problem is the velocity field of baryon gas. In some structure formation models, the velocity of IGM is assumed to follow the collapsing dark matter on scales larger than the Jeans length. Consequently, the IGM clouds with size on scales larger than the Jeans length will have collapsed, or be in the process of collapsing. However, it has been found that not all clouds with size larger than the Jeans length are in collapsing. The collapsing of the IGM clouds seems to be significantly suppressed with respect to the Jeans length at high redshifts (30). This effect leads to a suppression of formation of low mass collapsed clouds at high redshifts $z > 8$ (5). To understand this suppression, it is necessary to study the velocity field of the IGM on scales both larger and smaller than the Jeans length. Moreover, the temperature-velocity relation is often used to quantify collapsed (virialized or unvirialized) objects and so it is important to understand the temperature-velocity relation during the gravitational clustering.

### 3.1.3 Multiple phase of IGM thermal state

In simple model, the thermal state of the IGM is often assumed to be single phased, such as the temperature of modest density, like the Ly$\alpha$ forest absorption clouds is always $T \approx 10^{4-5}$ K, while the temperature of gas around groups and clusters would be $T \approx 10^{6-7}$ K. However, the IGM in proto-clusters and proto-groups at $z > 2$ probably is significantly multiphased (95). The large dispersion in the ratio of the densities HI and HeI given by the QSO’s absorption spectrum (43) also indicates that the IGM temperature probably is multiphased, i.e. it contains components with $T \approx 10^{3-4}$ K as well as with $T \approx 10^{4-5}$ K. If a minimum thermal broadening with temperature $2.4 \times 10^{4}$ K is applicable to all the IGM, all features or non-Gaussianities in the QSO’s absorption spectrum on scales $k > 0.1$ s/km should be erased. However, this result is challenged by the fact that the Ly$\alpha$ absorption transmitted flux on scales less than 20 km/s is still highly non-Gaussian (23; 39). To our view, the multiple phase of IGM thermal state is due to the dynamics of the far from equilibrium evolution.

Obviously, the formation of multiphase structures is difficult to be explained by analytical or semianalytical methods, as this method generally is to as-
sume that the relation between the temperature and density of IGM is of a single value, or at least is of statistically a single value. Two important questions emerge from this discussion, 1.) how do we describe an IGM that is multiphased in their thermal states; 2.) what dynamical evolution led the IGM to be multiple phased on large scales. One cannot study these problems without hydro simulation which can accurately capture the non-Gaussian features in both high and low density areas.

### 3.2 Turbulence-like behavior of cosmic baryon fluid

#### 3.2.1 The IGM as a Burgers’ fluids

Although the IGM is a Navier-Stokes fluid, and dynamically governed by the gravity of dark matter, it has been recognized that the growth modes of cosmic baryon gas in nonlinear regime is like Burgers fluid. The theory of Zeldovich’s pancake and the succeed adhesion model first indicated that the non-linear evolution of the gravitational clustering of cosmic matter can be sketched by a Burgers’ equation \((32)\). Considering that the cosmic matter is dissipative, the dynamical equation of the velocity field of the large scale structure is found essentially to be a variant of the random-force-driven Burgers equation or the KPZ equation \((3)\). Later, with a two-component (dark matter and baryon gas) generalization of the adhesion model, it was also found that the velocity potential of the baryon gas is described by the Burgers equation driven by the dark matter gravitational potential \((40; 53)\). Consequently, when the Reynolds number is large (in nonlinear regime, IGM generally is in this case), the Burgers turbulence will be developed. In the state of the Burgers turbulence, the fluid is filled with strong shocks. This phenomenon has not been carefully studied yet. It is not only important theoretically, but also related to many observable processes of the IGM, such as a.) the intermittency of the Ly\(\alpha\) transmitted flux; b.) the scaling of the probability distribution function (PDF) of the density and velocity distributions of the IGM.

#### 3.2.2 Intermittence of cosmic baryon fluid

We have showed that the velocity field of cosmic baryon fluid in the nonlinear regime is intermittent\((41)\). In the scale range from the Jeans length to about 16 \(h^{-1}\) Mpc, this field can be extremely well described by the She-Lévéque’s scaling formula. The baryon fluid also possesses the features: (1) for volume weight statistics, the dissipative structures are dominated by sheets, and (2) the relation between the intensities of fluctuations is hierarchical. These results imply that the evolution of highly evolved cosmic baryon fluid is similar to a fully developed turbulence\((74; 35)\). It actually is the so-called Burgers turbulence, in which the fluid is filled with shocks\((4; 53)\). Furthermore,
in the scale-free range, the non-Gaussian features of the mass density field of cosmic baryon fluid can be well described by a log-Poisson hierarchical cascade, which yields the She-Léveque’s scaling. All the predictions given by the log-Poisson RMP model, including the hierarchical relation, the order dependence of the intermittent exponent, the moments, and the scale-scale correlation, are in good agreement with the statistical results from 2nd to, at least, 12th orders of the samples of hydrodynamic simulation(47).

### 3.2.3 Observable effects of turbulence-like behavior of cosmic baryon fluid

We studied and will study the observable effects of the turbulence-like behavior. First, the higher order non-Gaussian behaviors of fluctuation field of Ly-α transmitted flux of quasar’s absorption will be used to compare simulation samples of transmitted flux(39; 62; 23; 96). The result will be useful to understand both the dynamical and thermal properties of hydrogen gas of IGM. Second, a comparison of the absorption features of HeII and HI of HE2347-4342 indicates that the absorption lines probably are turbulent-broadening(98). One has to study the effects of turbulence behavior of baryon gas on the broadening of the absorption lines(84; 49). Third, the maps of Sunyaev-Zeldovich effects(94), the polarization of CMB(37), etc. are determined by integral on electron density over line of sight, and therefore, the non-Gaussian features of these maps may also be affected by the turbulence-like behavior of IGM.
3.3 Physics of reionization epoch

The onset of the first generation star formation marks the time at which the Universe emerged from the so-called “Dark Ages” and is referred to as the epoch of reionization. The physics of the epoch of reionization is one of the most important topics in cosmology. It has attracted many theoretical investigations after the SDSS and WMAP showing some evidences of the reionization (22; 42). Hydrodynamics and radiative transfer are essential to study the formation of first stars and the reionization of neutral hydrogen clouds. How does the gas evolve from the state of primordial baryons to clustered clouds suitable to form the first generation stars? What are the major sources of heating neutral gas? How long did the history last from the first star formation to a full reionization? Can the clustering of primeval hydrogen gas be described by a similar mapping of the collapsing of dark matter? What are the statistical features of the spatial distributions of gaseous temperature and density of neutral and ionized hydrogen during the first star formation? What are the statistical features of the redshifted 21 cm emission of the neutral hydrogen? Preliminary theoretical investigations done by different groups, including ours, have shown that these problems are complicated (12; 33; 93; 37; 5; 44; 36). Although some analytical models can provide interesting results, but they are far from enough. A precise hydrodynamic simulation is necessary. In order to give theoretical predictions, which can be effectively tested with observations, reliable hydrodynamical simulation is crucial.

3.3.1 The growth of ionized and heated regions

There are also many studies on the evolution of radiation field. There are two approaches. The first is to describe the reionization with a rate equation of ionizing photons, i.e. the conservation equation of the ionizing photon number (75; 50; 54). The second approach is based on static radiative transfer, i.e. to drop the time derivative term of the radiative transfer equation, or to assume the speed of light is infinite (70; 1; 17; 31; 78; 57; 71; 13; 52; 76; 72; 38; 85; 91).

These codes are shortage in the following three aspects. 1. Their approximations would be reasonable only if the retardation effect is negligible. The retardation effect is not trivial. The time- and space-dependencies of the ionized region are substantially affected by the retardation (92; 77; 67; 68). This problem is more serious at high redshift, as the time scale of the retardation is comparable with the age of the universe (68). 2. The effects related to the time-dependence of photon’s frequency spectrum are omitted. However, For instance, to calculate the heating or the temperature profile if IGM around UV photon sources, the evolution of the photon distribution function in phase space is essential. 3. The dynamical behavior of cosmic baryon fluid
is treated separately with the evolution of radiation. This approximation is reasonable only if the time scale of photon’s retardation is much less than that of cosmic baryon fluid. However, it will not be so at high redshift epoch. It would also therefore be advantageous for the WENO algorithm, which can be the solver of evolution of baryon fluid in density and velocity spaces, and radiations in phase space.

The development of cosmology requires to have numerical solver for equations other than hydrodynamics and radiative transfer. For instance, some topics addressed in §2.6 below should be treated by the kinetics of Boltzmann equation, Fokker-Planck equation etc. The WENO scheme has found to be effective to deal with the Boltzmann-Poisson equations in semiconductor device simulations that we have successfully simulated using the WENO scheme for both the one dimensional (one space dimension, two phase dimension plus time) and two dimensional (two space dimension, three phase dimension plus time) situations (8; 9; 10). The WENO code developed in these references perform significantly better than other deterministic Boltzmann-Poisson solvers and produce results agreeing well with Monte-Carlo simulations. An eventual development of a WENO code for the kinetic equations would be very beneficial for the study of the early universe.

3.3.2 Absorption spectra of quasars at redshift \( z > 5 \)

The absorption spectra of quasars at redshift \( z > 5 \) consist of complete absorption troughs (Gunn-Peterson troughs) separated by tiny regions, which are Gunn-Peterson transparent and lead to Ly\( \alpha \) photon leaking(2; 22). The nature of the leaking is crucial to understand the physics of reionization. According to commonly accepted scenario of reionization, at early stage, only isolated patches around ionizing sources are highly ionized. The subsequent growing and overlapping of the ionizing patches lead to a uniform ionizing background and the end of reionization(17; 78; 30; 54). The ionization fraction of the IGM and the ionizing radiation underwent an evolution from highly non-uniform patches to a quasi-homogeneous field. Before the patch-to-uniform transition, only ionized patches would be transparent to Ly\( \alpha \) photons. After the transition, the low density voids will also be Gunn-Peterson transparent. Therefore, Ly\( \alpha \) leaks might have two origins: 1. the vestige of ionized patch around first generation stars and 2. low mass density areas of hydrogen gas at early universes. We proposal to study these two origins. We will, especially, investigate the following topics.

Since Ly\( \alpha \) absorption is very sensitive the remained neutral hydrogen in ionized patches, the details of the ionization profile is needed to study the properties of Ly\( \alpha \) leaks from the ionized patches. A detail calculation of the profile of ionized and heated patch is more important if considering the effect of damping wing of the neutral IGM absorption(55).
Ly\(\alpha\) leaks originate from low mass density areas (voids) would be important for cosmology, because the statistics of Ly\(\alpha\) leaks actually is the statistics of voids formed in the early universe. The size (or width) and its distribution of Ly\(\alpha\) leaks would be similar to the mass function of galactic clusters. One can expect that the size (width) distribution of voids would be able to yield effective constrain on cosmological parameters.

It has been pointed out that the transition of the ionization state of cosmic hydrogen is similar to a phase transition, and mean optical depth plays the role as order parameter\(^{(5, 45)}\). Therefore, one can expect, like phase transition in general, that the correlation length of the Ly\(\alpha\) underwent a dramatic evolution during the phase transition. Similarly, the evolution of temperature and its fluctuations of hydrogen gas will also be important in this epoch.

### 3.3.3 21 cm signal from early universe

Cosmic 21 cm signal is due to the decoupling of the spin temperature of neutral hydrogen atoms from the temperature of CMB. Therefore, the detection of redshifted 21 cm signals from the early universe is attracting many attentions in the study of cosmology\(^{(27, 36)}\). The 21 cm signals from individual UV ionizing sources in the reionization epoch may provide a direct identification of the ionized patches of the reionization\(^{(86, 15, 14, 46)}\). All these calculation rely on the so-called Wouthuysen-Field mechanism, which leads to the color temperature of the radiation spectrum near Ly\(\alpha\) frequency to be equal to the kinetic temperature of the baryonic gas if the resonant scattering of Ly\(\alpha\) photons by neutral hydrogen is effective. If there are enough Ly\(\alpha\) photons, the Wouthuysen-Field mechanism works well.

However, in the early universe, there are more questions about the 21 cm signal. For instance, whether there are correlation between the Ly\(\alpha\) leaks and 21 cm absorption, and whether died sources will left a 21 cm absorption region. These problems are of non-thermal equilibrium. It require a detail calculation of the evolution of the Ly\(\alpha\) photons in phase space caused by the resonant scattering. Since the resonant scattering will lead to rapid change of photon distribution function in frequency space, the WENO method would be advantaged.
3 Brief description
4 Publications (2005 - 2007)

Refereed journals


The nonlinear evolution of a system consisting of baryons and dark matter is generally characterized by strong shocks and discontinuities. The baryons slow down significantly at postshock areas of gravitational strong shocks, which can occur in high overdense as well as low overdense regions. Consequently, the baryon fraction would be nonuniform on large scales. We studied these phenomena with simulation samples produced by the WENO hybrid cosmological hydrodynamic/N-body code. We find that the baryon fraction in high mass density regions is lower on average than the cosmic baryon fraction, and many baryons accumulate in the regions with moderate mass density to form a high baryon fraction phase (HBFP). In dense regions with $\rho_{\Omega} > 100$, which are the possible hosts for galaxy clusters, the baryon fraction can be lower than the cosmic baryon fraction by about 10%–20% at $z = 0$. Our simulation samples show that about 3% of the cosmic baryon budget was hidden in the HBFP at redshift $z=3$, while this percentage increases to about 14% at the present day. The gas in the HBFP cannot be detected either by Ly-alpha forests of QSO absorption spectra or by soft X-ray background. That is, the HBFP would be missed in the baryon budget given by current observations.


The dynamic evolution of the baryonic intergalactic medium (IGM) caused by the underlying dark matter gravity is governed by the Navier-Stokes equations in which many cooling and heating processes are involved. However, it has long been recognized that the growth mode dynamics of cosmic matter clustering can be sketched by a random force driven Burgers’ equation if cooling and heating are ignored. Just how well the dynamics of the IGM can be described as a Burgers fluid has not been fully investigated probably because cooling and heating are essential for a detailed understanding of the IGM. Using IGM samples produced by a cosmological hydrodynamic simulation in which heating and cooling processes are properly accounted for, we show that the IGM velocity field in the nonlinear regime shows the features of a Burgers fluid, that is, when the Reynolds number is high, the velocity field consists
of an ensemble of shocks. Consequently, (1) the IGM velocity $v$ is generally smaller than that of dark matter; (2) for the smoothed field, the IGM velocity shows tight correlation with dark matter given by $v \simeq sv_{dm}$, with $s < 1$, such that the lower the redshift, the smaller $s$; (3) the velocity PDFs are asymmetric between acceleration and deceleration events; (4) the PDF of velocity difference $\Delta v = v(x + r) - v(x)$ satisfies the scaling relation for a Burgers fluid, i.e., $P(\Delta v) = (1/r^3)F(\Delta v/r^6)$. We find the scaling function and parameters for the IGM which are applicable to the entire scale range of the samples ($0.26 - 8 \, h^{-1} \, \text{Mpc}$). These properties show that the similarity mapping between the IGM and dark matter is violated on scales much larger than the Jeans length of the IGM.


We show that, in the halo model of large-scale structure formation, the difference between the Fourier and the DWT (discrete wavelet transform) power spectra provides a statistical measurement of the halos. This statistical quantity is free from parameters related to the shape of the mass profile and the identification scheme of halos. That is, the statistical measurement is invariant in the sense that models with reasonably defined and selected parameters of the halo models should yield the same difference of the Fourier and DWT spectra. This feature is useful to extract ensemble averaged properties of halos, which cannot be obtained with the identification of individual halo. To demonstrate this point, we show with WIGEON hydrodynamical simulation samples that the spectrum difference provides a quantitative measurement of the discrepancy of the distribution of baryonic gas from that of the underlying dark matter field within halos. We also show that the mass density profile of halos in physical space can be reconstructed with this statistical measurement. This profile essentially is the average over an ensemble of halos, including well virialized halos as well as halos with significant internal substructures. Moreover, this reconstruction is sensitive to the tail of the mass density profile. We showed that the profile with $1/r^3$ tail gives very different result from that of $1/r^2$. Other possible applications of this method are discussed as well.


We have studied the power spectrum and the intermittent behavior of the fluctuations in the transmitted flux of HE2347-4342 Lyα absorption in order to investigate if there is any discrepancy between the LCDM model with parameters given by the WMAP and observations on small scales. If the non-Gaussianity of cosmic mass field is assumed to come only from halos with an universal mass profile of the LCDM model, the non-Gaussian behavior of mass field would be effectively measured by its intermittency, because intermittency
is a basic statistical feature of the cuspy structures. We have shown that the Lyα transmitted flux field of HE2347-4342 is significantly intermittent on small scales. With the hydrodynamic simulation, we demonstrate that the LCDM model is successful in explaining the power spectrum and intermittency of Lyα transmitted flux. Using statistics ranging from the second to eighth order, we find no discrepancy between the LCDM model and the observed transmitted flux field, and no evidence to support the necessity of reducing the power of density perturbations relative to the standard LCDM model up to comoving scales as small as about 0.08h⁻¹Mpc. Moreover, our simulation samples show that the intermittent exponent of the Lyα transmitted flux field is probably scale-dependent. This result is different from the prediction of universal mass profile with a constant index of the central cusp. The scale-dependence of the intermittent exponent indicates that the distribution of baryonic gas is decoupled from the underlying dark matter.


We investigate the statistical properties of cosmic baryon fluid in the nonlinear regime, which is crucial for understanding the large-scale structure formation of the universe. With the hydrodynamic simulation sample of the Universe in the cold dark matter model with a cosmological constant, we show that the intermittency of the velocity field of cosmic baryon fluid at redshift z=0 in the scale range from the Jeans length to about 16 Mpc/h can be extremely well described by She-Leveque’s universal scaling formula. The baryon fluid also possesses the following features: (1) for volume weight statistics, the dissipative structures are dominated by sheets, and (2) the relation between the intensities of fluctuations is hierarchical. These results imply that the evolution of highly evolved cosmic baryon fluid is similar to a fully developed turbulence.


We study the X-ray emission of baryon fluid in the universe using the WIGEON cosmological hydrodynamic simulations. It has been revealed that cosmic baryon fluid in the nonlinear regime behaves like Burgers turbulence, i.e. the fluid field consists of shocks. Like turbulence in incompressible fluid, the Burgers turbulence plays an important role in converting the kinetic energy of the fluid to thermal energy and heats the gas. We show that the simulation sample of the ΛCDM model without adding extra heating sources can fit well the observed distributions of X-ray luminosity versus temperature (L_x vs. T) of galaxy groups and is also consistent with the distributions of X-ray luminosity versus velocity dispersion (L_x vs. σ). Because the baryonic gas is multiphase, the L_x – T and L_x – σ distributions are significantly scattered. If we describe
Figure 4.1: X-ray luminosity $L_x$ vs. temperature $T$ for simulation (black) at redshift $z = 0$ with the DWT decomposition on scales $0.78 \, h^{-1}$ Mpc. Three sets of observed data are shown by square, circle and triangle.

the relationships by power laws $L_x \propto T^{\alpha_L}$ and $L_x \propto \sigma^{\alpha_L}$, we find $\alpha_L \geq 2.5$ and $\alpha_L \geq 2.1$. The X-ray background in the soft $0.5 - 2$ keV band emitted by the baryonic gas in the temperature range $10^5 < T < 10^7$ K has also been calculated. We show that of the total background, (1) no more than 2% comes from the region with temperature less than $10^6.5$ K, and (2) no more than 7% is from the region of dark matter with mass density $\rho_{\text{dm}} < 50 \bar{\rho}_{\text{dm}}$. The region of $\rho_{\text{dm}} > 50 \bar{\rho}_{\text{dm}}$ is generally clustered and discretely distributed. Therefore, almost all of the soft X-ray background comes from clustered sources, and the contribution from truly diffuse gas is probably negligible. This point agrees with current X-ray observations.


We study the SZ-effect-induced non-Gaussianity in the cosmic microwave background (CMB) fluctuation maps. If a CMB map is contaminated by the SZ effect of galaxies or galaxy clusters, the CMB maps should have similar non-Gaussian features as the galaxy and cluster fields. Using the WMAP data and 2MASS galaxy catalog we show that the non-Gaussianity of the 2MASS galaxies is imprinted on WMAP maps. The signature of non-Gaussianity can be seen with the $4^{th}$ order cross correlation between the wavelet variables of the WMAP maps and 2MASS clusters. The intensity of the $4^{th}$ order non-Gaussian features is found to be consistent with the contamination of the SZ effect of 2MASS galaxies. We also show that this non-Gaussianity can not be seen by the high order auto-correlation of the WMAP. This is because the SZ signals in
the auto-correlations of the WMAP data generally is weaker than the WMAP-2MASS cross correlations by a factor $f^2$, which is the ratio between the powers of SZ effect map and the CMB fluctuations on the scale considered. Therefore, the ratio of high order auto-correlations of CMB maps to cross-correlations of the CMB maps and galaxy field would be effective to constrain the powers of SZ effect on various scales.


We study the Gunn-Peterson effect of the photo-ionized intergalactic medium (IGM) in the redshift range $5 < z < 6.4$ using semi-analytic simulations based on the log-normal model. Assuming a rapidly evolved and spatially uniform ionizing background, the simulation can produce all the observed abnormal statistical features near redshift $z = 6$. They include: 1) rapidly increase of absorption depths; 2) large scatter in the optical depths; 3) long-tailed distributions of transmitted flux and 4) long dark gaps in spectra. These abnormal features are mainly due to rare events, which correspond to the long-tailed probability distribution of the IGM density field, and therefore, they may not imply significantly spatial fluctuations in the UV ionizing background at $z = 6$.


Using cosmological hydrodynamic simulations of the LCDM model, we present a comparison between the simulation sample and real data sample of HI and HeII Ly$\alpha$ transmitted flux in the absorption spectra of the QSO HE2347-4342. The LCDM model is successful in simultaneously explaining the statistical features of both HI and HeII Ly$\alpha$ transmitted flux. It includes: 1.) the power spectra of the transmitted flux of HI and HeII can be well fitted on all scales $\zeta 0.28 h^{-1}$ Mpc for H, and $\zeta 1.1 h^{-1}$ Mpc for He; 2.) the Doppler parameters of absorption features of HeII and HI are found to be turbulent-broadening; 3.) the ratio of HeII to HI optical depths are substantially scattered, due to the significant effect of noise. A large part of the $\eta$-scatter is due to the noise in the HeII flux. However, the real data contain more low-$\eta$ events than simulation sample. This discrepancy may indicate that the mechanism leading extra fluctuations upon the simulation data, such as a fluctuating UV radiation background, is needed. Yet, models of these extra fluctuations should satisfy the constraints: 1.) if the fluctuations are Gaussian, they should be limited by the power spectra of observed HI and HeII flux; 2.) if the fluctuations are non-Gaussian, they should be limited by the observed non-Gaussian features of the HI and HeII flux.

10. A WENO algorithm for the radiative transfer and ionized sphere at
We show that the algorithm based on the weighted essentially nonoscillatory (WENO) scheme with anti-diffusive flux corrections can be used as a solver of the radiative transfer equations. This algorithm is highly stable and robust for solving problems with both discontinuities and smooth solution structures. We test this code with the ionized sphere around point sources. It shows that the WENO scheme can reveal the discontinuity of the radiative or ionizing fronts as well as the evolution of photon frequency spectrum with high accuracy on coarse meshes and for a very wide parameter space. This method would be useful to study the details of the ionized patch given by individual source in the epoch of reionization. We demonstrate this method by calculating the evolution of the ionized sphere around point sources in physical and frequency spaces. It shows that the profile of the fraction of neutral hydrogen and the ionized radius are sensitively dependent on the intensity of the source.


We develop a numerical solver for radiative transfer problems based on the weighted essentially nonoscillatory (WENO) scheme modified with anti-diffusive flux corrections, in order to solve the temperature and ionization profiles around a point source of photons in the reionization epoch. Algorithms for such simulation must be able to handle the following two features: 1. the sharp profiles of ionization and temperature at the ionizing front (I-front) and the heating front (T-front), and 2. the fraction of neutral hydrogen within the ionized sphere is extremely small due to the stiffness of the rate equations of atom processes. The WENO scheme can properly handle these two features, as it has been shown to have high order of accuracy and good convergence in capturing discontinuities and complicated structures in fluid as well as to be significantly superior over piecewise smooth solutions containing discontinuities. With this algorithm, we show the time-dependence of the preheated shell around a UV photon source. In the first stage the I-front and T-front are coincident, and propagate with almost the speed of light. In later stage, when the frequency spectrum of UV photons is hardened, the speeds of propagation of the ionizing and heating fronts are both significantly less than the speed of light, and the heating front is always beyond the ionizing front. In the spherical shell between the I- and T-fronts, the IGM is heated, while atoms keep almost neutral. The time scale of the preheated shell evolution is dependent on the intensity of the photon source. We also find that the details of the pre-heated shell and the distribution of neutral hydrogen remained in the ionized sphere are actually sensitive to the parameters used. The WENO algorithm can provide stable and robust solutions to study these details.

Abstract: We estimate the power spectrum of SZ(Sunyaev-Zel’dovich)-effect-induced temperature fluctuations on sub-degree scales by using the cross correlation between the three-year WMAP maps and 2MASS galaxy distribution. We produced the SZ effect maps by hydrodynamic simulation samples of the ΛCDM model, and show that the SZ effect temperature fluctuations are highly non-Gaussian. The PDF of the temperature fluctuations has a long tail. More than 70% power of the SZ effect temperature fluctuations attributes to top \( \sim 1\% \) wavelet modes (long tail events). On the other hand, the CMB temperature fluctuations basically are Gaussian. Although the mean power of CMB temperature fluctuations on sub-degree scales is much higher than that of SZ effect map, the SZ effect temperature fluctuations associated with top 2MASS clusters is comparable to the power of CMB temperature fluctuations on the same scales. Thus, from noisy WMAP maps, one can have a proper estimation of the SZ effect power at the positions of the top 2MASS clusters. The power spectrum given by these top wavelet modes is useful to constrain the parameter of density fluctuations amplitude \( \sigma_8 \). We find that the power spectrum of these top wavelet modes of SZ effect on sub-degree scales basically is consistent with the simulation maps produced with \( \sigma_8 = 0.84 \). The simulation samples of \( \sigma_8 = 0.74 \) show, however, significant deviation from detected SZ power spectrum. It can be ruled out with confidence level 99% if all other cosmological parameters are the same as that given by the three-year WMAP results.

13. 21 cm signals from early ionizing sources, J. R. Liu, J.M. Qiu, L. L. Feng, C. W. Shu and L.Z. Fang *Astrophys. J.*, 663, 1

We investigate the 21 cm signals from the UV ionizing sources in the reionization epoch. The formation and evolution of 21 cm emission and absorption regions depend essentially on the kinetics of photons in the physical and frequency spaces. To solve the radiative transfer equation, we use the WENO algorithm, which is effective to capture the sharp ionization profile and the cut-off at the front of light \( (r = ct) \) and to handle the small fraction of neutral hydrogen and helium in the ionized sphere. We show that a spherical shell of 21 cm emission and absorption will develop around a point source once the speed of the ionization front (I-front) is significantly lower than the speed of light. The 21 cm shell extends from the I-front to the front of light; its inner part is the emission region and its outer part is the absorption region. The 21 cm emission region depends strongly on the intensity, frequency-spectrum and life-time of the UV ionizing source. For a source of short life-time, no 21 cm emission region can be formed if the source dies out before the I-front speed is significantly lower than the speed of light. Yet, a 21 cm absorption region can
form and develop even after the emission of the source ceases.


We investigate the volume growth of ionized regions around UV photon sources with the WENO algorithm, which is an effective solver of photon kinetics in the phase space described by the radiative transfer equation. We show that the volume growth rate, either of isolated ionized regions or of clustered regions in merging, generally consists of three phases: fast or relativistic growth phase at the early stage, slow growth phase at the later stage, and a transition phase between the fast and slow phases. We also show that the volume growth of ionized regions around clustered sources with intensity $\dot{E}_i \ (i = 1,2,...)$ would have the same behavior as a single source with intensity $\dot{E} = \sum_i \dot{E}_i$, if all the distances between nearest neighbor sources $i$ and $j$ are smaller than $c(t_i^c + t_j^c)$, $t_i^c$ being the time scale $t_c$ of source $i$. Therefore, a tightly clustered UV photon sources would lead to a slow growth of ionized volume. This effect would be important for studying the redshift-dependence of 21cm signals from the reionization epoch.


In the nonlinear regime of cosmic clustering, the mass density field of the cosmic baryon fluid is highly non-Gaussian. It shows different dynamical behavior from collisionless dark matter. Nevertheless, the evolved field of baryon fluid is scale-covariant in the range from the Jeans length to a few ten $h^{-1}$ Mpc, in which the dynamical equations and initial perturbations are scale free. We show that in the scale-free range, the non-Gaussian features of the cosmic baryon fluid, governed by the Navier-Stokes equation in an expanding universe, can be well described by a log-Poisson hierarchical cascade. The log-Poisson scheme is a random multiplicative process (RMP), which causes non-Gaussianity and intermittency even when the original field is Gaussian. The log-Poisson RMP contains two dimensionless parameters: $\beta$ for the intermittency and $\gamma$ for the most singular structure. All the predictions given by the log-Poisson RMP model, including the hierarchical relation, the order dependence of the intermittent exponent, the moments, and the scale-scale correlation, are in good agreement with the results given by hydrodynamic simulations of the standard cold dark matter model. The intermittent parameter $\beta$ decreases slightly at low redshift and indicates that the density field of baryon fluid contains more singular structures at lower redshifts. The applicability of the model is addressed.

Spectra of high redshift QSOs show deep Gunn-Peterson absorptions on the blue sides of the Lyα emissions lines. They can be decomposed into components called Lyα leaks, defined to be emissive regions in complementary to otherwise zero-fluxed absorption gaps. Just like Lyα absorption forests at low redshifts, Lyα leaks are both easy to find in observations and containing rich sets of statistical properties that can be used to study the early evolution of the IGM. Among all properties of a leak profile, we investigate its equivalent width in this paper, since it is weakly affected by instrumental resolution and noise. Using 10 Keck QSO spectra at \( z \sim 6 \), we have measured the number density distribution function \( n(W, z) \), defined to be the number of leaks per equivalent width \( W \) and per redshift \( z \), in the redshift range \( 5.4 - 6.0 \). These new observational statistics, in both the differential and cumulative forms, fit well to hydro numerical simulations of uniform ionizing background in the \( \Lambda \)CDM cosmology. In this model, Lyα leaks are mainly due to low density voids. It supports the early studies that the IGM at \( z \sim 6 \) would still be in a highly ionized state with neutral hydrogen fraction \( \sim 10^{-4} \). Measurements of \( n(W, z) \) at \( z > 6 \) would be effective to probe the reionization of the IGM.


Lyα absorption spectra of QSOs at redshifts \( z \sim 6 \) show complete Gunn-Peterson absorption troughs (dark gaps) separated by tiny leaks. The dark gaps are from the intergalactic medium (IGM) where the density of neutral hydrogen are high enough to produce almost saturated absorptions, however, where the transmitted leaks come from is still unclear so far. We demonstrate that leaking can originate from the lowest density voids in the IGM as well as the ionized patches around ionizing sources using semi-analytical simulations. If leaks were produced in lowest density voids, the IGM might already be highly ionized, and the ionizing background should be almost uniform; in contrast, if leaks come from ionized patches, the neutral fraction of IGM would be still high, and the ionizing background is significantly inhomogeneous. Therefore, the origin of leaking is crucial to determining the epoch of inhomogeneous-to-uniform transition of the the ionizing photon background. We show that the origin could be studied with the statistical features of leaks. Actually, Lyα leaks can be well defined and described by the equivalent width \( W \) and the full width of half area \( W_{1/2} \), both of which are less contaminated by instrumental resolution and noise. It is found that the distribution of \( W \) and \( W_{1/2} \) of Lyα leaks are sensitive to the modeling of the ionizing background. We consider four representative reionization models. It is concluded that the leak statistics provides an effective tool to probe the evolutionary history of reionization at \( z \sim 5 - 6.5 \). Similar statistics would also be applicable to the reionization of He II at \( z \sim 3 \).

2. Long-tailed time-dependent correlation of primordial cosmic perturbations in the inflationary cosmology and its observable effects, L.Z. Fang, in *Inquiring the Universe: Essays to celebrate Professor Mario Novellon jubilee*, Frontier Groups, (ISBN 2914601085)


**Invited talks at international conferences**

1. Colloquium: Turbulence-like behavior of cosmic baryon fluid and cosmological hydrodynamical simulation, Brown University, October 28, 2005

2. Public talk: When would the sky fall? July 20, 2005 Seoul C Mt. Kumgang, Korea

3. Invited talk: Abnormal features of cosmic temperature fluctuations. 14 June 2005, Pescara, Italy


5. Invited talk: chronology of the dark ages of the universe, June 20, 2005, Seoul-Mt. Kumgang, Korea

6. Invited talk: Stories of SN 1006 in ancient Chinese literatures. 11 July 2006, meeting on “Supernova, GRB and cosmology” Pescara, Italy

7. Invited talk: Non-linear evolution of cosmic baryon fluid 13 July 2006, on “Supernova, GRB and cosmology” Pescara, Italy


9. Invited talk: 21 cm signals from ionized and heated regions around first stars, 4th Italian-Sino workshop on relativistic astrophysics, 23 July 2007

10. Invited talk: The standard cosmological model, Taipei School/Workshop on Large Scale Structures of the Universe National Center for Theoretical Sciences, May 28 C June 2, 2007

11. Invited talk: primordial perturbations, Taipei School/Workshop on Large Scale Structures of the Universe National Center for Theoretical Sciences, May 28 C June 2, 2007
12. Invited talk: nonlinear evolution of intergalactic medium (IGM), Taipei School/Workshop on Large Scale Structures of the Universe National Center for Theoretical Sciences, May 28 C June 2, 2007

13. Invited talk: probe of dark energy with large scale structures, Taipei School/Workshop on Large Scale Structures of the Universe National Center for Theoretical Sciences, May 28 C June 2, 2007
Bibliography


[31] N. Gnedin; T. Abel, Multi-dimensional cosmological radiative transfer with a Variable Eddington Tensor formalism, New Astronomy, 6, (2001), 437


Bibliography


