Cosmology and Large Scale Structures

1 Topics

- Simulation of cosmological hydrodynamics and kinetics
  - WENO scheme of cosmological hydrodynamic simulation
  - Kinetics of photons with resonant scattering
- Turbulence behavior of cosmic baryon fluid
  - Intermittence of cosmic baryon fluid
  - Observable effects of turbulence behavior of cosmic baryon fluid: scaling relations
- Physics of reionization epoch
  - 21 cm emission and absorption from early universe
  - Cosmology of leaking features of high redshift quasar's absorption spectrum

2 Participants

2.1 Participants from University of Arizona

- Li-Zhi Fang
- Ji-Ren Liu
- Yi Lu

2.2 Collaborators

- Hong-Guan Bi (urple 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 Hopkings University, USA)

2.3 Students

- Liang Cao (University of Arizona, USA)
- Jian-Mai Qiu (Brown University, USA)
- Ishani Roy (Brown University, USA)
- Qiang Yuan (The institute of High Energy Physics, Beijing)

3 Brief description

3.1 Simulation method of cosmological hydrodynamics and kinetics

3.1.1 WENO schemes

WENO schemes are a class of high order numerical methods for solving partial differential equations whose solutions may contain discontinuities, sharp gradient regions, and other complex solution structures. Such partial differential equations include the Euler equations or high Reynolds number Navier-Stokes equations which appear often in astronomical applications. WENO schemes are designed based on the successful essentially non-oscillatory (ENO) schemes in Harten, Engquist, Osher and Chakravarthy (37) and Shu and Osher (89; 90). The first WENO scheme was constructed in Liu, Osher and Chan (58) for a third order finite volume version in one space dimension. In Jiang and Shu (45), third and fifth order finite difference WENO schemes in multi space dimensions are constructed, with a general framework for the design of the smoothness indicators and nonlinear weights. Later developments and applications of WENO schemes mostly follow the approach in (45). Very high order finite difference WENO schemes (for orders between 7 and 11) have been developed in Balsara and Shu (2). Finite volume WENO schemes for 2D general triangulation have been developed in Friedrichs (25) and in Hu and Shu (41).

Both ENO and WENO schemes use the idea of adaptive stencils in the reconstruction procedure based on the local smoothness of the numerical solution to automatically achieve high order accuracy and non-oscillatory property near discontinuities. ENO uses just one (optimal in some sense) out of many candidate stencils when doing the reconstruction; while WENO uses a convex combination of all the candidate stencils, each being assigned a nonlinear weight which depends on the local smoothness of the numerical solution based on that stencil. WENO improves upon ENO in robustness, better smoothness of fluxes, better steady state convergence, better provable convergence properties, and more efficiency. For more details of ENO and WENO schemes, we refer to the lecture notes (87; 88).

WENO schemes have been widely used in applications. Some of the examples include dynamical response of a stellar atmosphere to pressure perturbations (19); shock vortex interactions and other gas dynamics problems

(32), (33); incompressible flow problems (104); Hamilton-Jacobi equations (44); magneto-hydrodynamics (46); underwater blast-wave focusing (50); the composite schemes and shallow water equations (51), (52), real gas computations (65).

3.1.2 WENO method of cosmological hydrodynamics

Though the universe seems to be dominated by the dark sides of both matter and energy (98), the observed luminous universe has been existing in the form of baryonic matter, whose mass density, constrained by the primordial nucleosynthesis (99), 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 (66), intergalactic medium inferred from Lyα forest (77), X-ray background radiation (28) and distorted spectrum of the cosmic background radiation due to the Sunyaev-Zeldovich effect (105; 70), 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. (5; 26; 60).

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 (24). 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. (93; 94). 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 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:

method	Sedov Blast wave	Zeldovich pancake
1. Bryan (8)	N/A	pass
2. Cen (Ryu) (81)	N/A	pass
3. Couchman (18)	fail	N/A
4. Evrard (20)	N/A	N/A
5. Gnedin (29)	N/A	N/A
6. Jenkins (73)	N/A	N/A
7. Navarro (68)	N/A	N/A
8. Owen (71)	pass	N/A
9. Pen (74)	pass	pass
10. Steinmetz (92)	N/A	N/A
11. Warren (100)	N/A	N/A
12. Springel (94)	pass	N/A
13. WENO	pass	pass

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 (7; 69). For the Eulerian approach in numerical cosmology, the better codes are based on the high resolution shock capturing total-variation diminishing (TVD) scheme (Harten (36)) 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 (86; 107), 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 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 (9; 10; 11). 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 (23).

3.1.3 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(83; 59; 63). The second approach is based on static radiative transfer, i.e. to drop the time derivative term of the radiative transfer equation, ot to assume the speed of light is infinite(78; 1; 17; 31; 91; 67; 79; 13; 61; 84; 80; 42; 96; 101).

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(102; 85; 75; 76). This problem is more serious at high redshift, as the time scale of the retardation is comparable with the age of the universe (76). 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 it 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.

3.1.4 Kinetics of photons with resonant scattering

The development of cosmology requires to have numerical solver for equations other than hydrodynamics and radiative transfer. Some topics 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 (9; 10; 11). 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.

All these calculation rely on the so-called Wouthuysen-Field mechanism, which leads to the color temperature of the radiation spectrum near Lyα frequency to be equal to the kinetic temperature of the baryonic gas if the resonant scattering of Lyα photons by neutral hydrogen is effective. If there are enough Lyα photons, the Wouthuysen-Field mechanism works well.

3.2 Turbulence behavior of cosmic baryon fluid

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 (34). 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 (4). 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 (47; 62). 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 Lyα transmitted flux; b.) the scaling of the probability distribution function (PDF) of the density and velocity distributions of the IGM.

3.2.1 Intermittence of cosmic baryon fluid

We have showed that the velocity field of cosmic baryon fluid in the nonlinear regime is intermittent(48). In the scale range from the Jeans length to about 16 h^{-1} Mpc, this field can be extremely well described by the She-Lévěque'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(82; 38). It actually is the so-called Burgers turbulence, in which the fluid is filled with shocks(4; 62). 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-Lévěque'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(56).

3.2.2 Observable effects of turbulence behavior of cosmic baryon fluid: scaling relations

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 comapre simulation samples of transmitted flux(43; 72; 22; 106). The result will be useful to understand both the dynamical and thermal properties of hydrogen gas of IGM. Second, a comparason of the absorption features of HeII and HI of HE2347-4342 indicates that the absorption lines probably are turbulent-broadening(108). One has to study the effects of turbulence behavior of baryon gas on the broading of the absorption lines(95; 57). third, the maps of Sunyaev-Zeldovich effects(105), the polarization of CMB(40), 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 (21; 49). 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; 35; 103; 40; 6; 53; 39). Although simeanalytical 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 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; 39). 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(97; 15; 14; 55). All these calculation rely on the so-called Wouthuysen-Field mechanism, which leads to the color temperature of the radiation spectrum near Lyα frequency to be equal to the kinetic temperature of the baryonic gas if the resonant scattering of Lyα photons by neutral hydrogen is effective. If there are enough Lyα 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 Lyα 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 Lyα 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.

3.3.2 Cosmology of leaking of high redshift quasar's absorption spectrum

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 Lyα photon leaking(3; 21). 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; 91; 30; 63). 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 Lyα photons. After the transition, the low density voids will also be Gunn-Peterson transparent. Therefore, Lyα 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 Lyα absorption is very sensitive the remained neutral hydrogen in ionized patches, the details of the ionization proifile is needed to study the properties of Lyα 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(64).

Lyα leaks originate from low mass density areas (voids) would be important for cosmology, because the statistics of Lyα leaks actually is the statistics of voids formed in the early universe. The size (or width) and its distribution of Lyα leaks would be similar to the mass function of galactic clusters. One can expect that the zise (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 similar to a phase transition, and mean optical depth plays the role as order parameter(6; 54). Therefore, one can expect, like phase transition in general, that the correlation length of the Lyα 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.

Bibliography

[1] T. Abel; M. Norman; P. Madau, Photon-conserving Radiative Transfer around Point Sources in Multidimensional Numerical Cosmology, ApJ, 523, (1999), 66.

[2] D. Balsara and C.-W. Shu, *Monotonicity preserving weighted essentially non-oscillatory schemes with increasingly high order of accuracy*, Journal of Computational Physics, v160 (2000), pp.405-452.

[3] R. Becker, et al. Evidence for Reionization at z 6: Detection of a Gunn-Peterson Trough in a z=6.28 Quasar, AJ, 122, (2001), 2850.

[4] A. Berera, & L.Z. Fang, Stochastic fluctuations and structure formation in the universe, Phys. Rev. Lett., 72, (1994), 458

[5] E. Bertschinger, *Simulations of structure formation in the universe*, Annual Review of Astronomy and Astrophysics, v36 (1998), pp.599-654.

[6] H.G. Bi, L.Z. Fang, L.L. Feng, and Y.P. Jing, Hydrogen Clouds before Reionization: A Lognormal Model Approach, ApJ, 598, (2003), 1.

[7] S. Borve, M. Omang, and J. Trulsen, Regularized Smoothed Particle Hydrodynamics: A New Approach to Simulating Magnetohydrodynamic Shocks, ApJ, 561, (2001), 82

[8] G.L. Bryan, M.L. Norman, J.M. Stone, R. Cen and J.P. Ostriker, *A piecewise parabolic method for cosmological hydrodynamics*, Computer Physics Communications, v89 (1995), pp.149-168.

[9] J.A. Carrillo, I.M. Gamba, A. Majorana and C.-W. Shu, *A WENO-solver for the 1D non-stationary Boltzmann-Poisson system for semiconductor devices*, Journal of Computational Electronics, v1 (2002), pp.365-370.

[10] J.A. Carrillo, I.M. Gamba, A. Majorana and C.-W. Shu, *A WENO-solver for the transients of Boltzmann–Poisson system for semiconductor devices. Performance and comparisons with Monte Carlo methods*, Journal of Computational Physics, v184 (2003), pp.498-525.

[11] J. Carrillo, I. Gamba, A. Majorana and C.-W. Shu, *A direct solver for 2D non-stationary Boltzmann-Poisson systems for semiconductor devices: a MESFET simulation by WENO-Boltzmann schemes*, Journal of Computational Electronics, v2 (2003), pp.375-380.

[12] R.Y. Cen, The Universe Was Reionized Twice, ApJ, 591, (2003), 12

[13] R. Cen, A Fast, Accurate, and Robust Algorithm for Transferring Radiation in Three-dimensional Space, ApJS, 141, 211.

[14] R. Cen, Detection and Fundamental Applications of Individual First Galaxies ApJ, 648, (2006), 47.

[15] L. Chuzhoy; M. Alvarez; P. Shapiro, Recognizing the First Radiation Sources through Their 21 cm Signature ApJ, 648, (2006), 1.

[16] P. Colella and P.R. Woodward, *The piecewise-parabolic method (PPM) for gas-dynamical simulations*, Journal of Computational Physics, v54 (1984), pp.174-201.

[17] B. Ciardi; A. Ferrara; S. Marri; G. Raimondo, Cosmological reionization around the first stars: Monte Carlo radiative transfer, MNRAS, 324, (2001), 381.

[18] H. Couchman, P. Thomas, F. Pearce, Hydra: an Adaptive-Mesh Implementation of P 3M-SPH, ApJ, 452, (1995) 797.

[19] L. Del Zanna, M. Velli and P. Londrillo, *Dynamical response of a stellar atmosphere to pressure perturbations: numerical simulations*, Astron. Astrophys., v330 (1998), pp.L13-L16.

[20] A. Evrard, Beyond N-body - 3D cosmological gas dynamics, MNRAS, 235, (1988), 911

[21] , X. Fan, et al. Constraining the Evolution of the Ionizing Background and the Epoch of Reionization with z 6 Quasars. II. A Sample of 19 Quasars, AJ, 132, (2006), 117.

[22] L. L. Feng, J. Pando, and L. Z. Fang, Intermittent features of the QSO Lyα transmitted flux: results from hydrodynamic cosmological simulations, Astrophys. J., 587, (2003), 487.

[23] L.-L. Feng, C.-W. Shu and M. Zhang, *A hybrid cosmological hydrodynamic/N-body code based on a weighted essentially non-oscillatory scheme*, Astrophysical Journal, v612 (2004), pp.1-13.

[24] C. Frenk, S. White, P. Bode, J. Bond, G. Bryan, R. Cen, H. Couchman, A. Evrard, N. Gnedin, A. Jenkins, A. Khokhlov, A. Klypin, J. Navarro, M. Norman, J. Ostriker, J Owen, F Pearce, U. Pen, M. Steinmetz, P. Thomas, J. Villumsen, J. Wadsley, M. Warren, G. Xu, G. Yepes, The Santa Barbara Cluster Comparison Project: A Comparison of Cosmological Hydrodynamics Solutions, ApJ, 525, (1999), 554

[25] O. Friedrichs, *Weighted essentially non-oscillatory schemes for the interpolation of mean values on unstructured grids*, Journal of Computational Physics, v144 (1998), pp.194-212.

[26] J.A. Font, *Numerical hydrodynamics in general relativity*, Living Rev. Relativity, 6, (2003), 4. Online Article: cited November 1, 2004, http://www.livingreviews.org/lrr-2003-4

[27] S. Furlanetto; S. Oh; F. Briggs, Cosmology at low frequencies: The 21 cm transition and the high-redshift Universe Physics Report, 433, (2006), 181.

[28] R. Giacconi, H. Gursky, F. Paolini and B. Rossi, Evidence for x Rays From Sources Outside the Solar System, Physical Review Letters, v9 (1962), pp.439.

[29] N. Gnedin, Softened Lagrangian hydrodynamics for cosmology, ApJS, 97, (1995), 231

[30] N.Y. Gnedin, Effect of Reionization on the Structure Formation in the Universe, ApJ, 542, (2000), 535.

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

[32] F. Grasso and S. Pirozzoli, *Shock-wave-vortex interactions: Shock and vortex deformations, and sound production*, Theor. Comp. Fluid Dyn., v13 (2000), pp.421-456.

[33] F. Grasso and S. Pirozzoli, *Shock wave-thermal inhomogeneity interactions: Analysis and numerical simulations of sound generation*, Phys. Fluids, v12 (2000), pp.205-219.

[34] S. Gurbatov, A. Saichev, S. Shandarin, The large-scale structure of the universe in the frame of the model equation of non-linear diffusion, MNRAS, 236, (1989) 385

[35] Z. Haiman, and G. Holder, G. The Reionization History at High Redshifts I: Physical Models and New Constraints from CMB Polarization, ApJ, 595, (2003), 1

[36] A. Harten, *High resolution schemes for hyperbolic conservation laws*, Journal of Computational Physics, v49 (1983), pp.357-393.

[37] A. Harten, B. Engquist, S. Osher and S. Chakravarthy, *Uniformly high order essentially non-oscillatory schemes, III*, Journal of Computational Physics, v71 (1987), pp.231-303.

[38] P. He; J.R. Liu; L.L. Feng; C-W. Shu; L.Z.Fang, Li-Zhi, Low-Redshift Cosmic Baryon Fluid on Large Scales and She-Leveque Universal Scaling Phys. Rev. Lett. 96, (2006), 1302.

[39] P. He, J. Liu, L.-L. Feng, H.-G. Bi, & L.Z. Fang, Statistical Features of 21 Centimeter Emission from the Epoch between Reionization and the Gunn-Peterson Transparency ApJ, 614, (2004), 6

[40] G. Holder, Z. Haiman, M. Kaplinghat, and L. Knox, The Reionization History at High Redshifts II: Estimating the Optical Depth to Thomson Scattering from CMB Polarization, ApJ, 595, (2003), 13.

[41] C. Hu and C.-W. Shu, *Weighted essentially non-oscillatory schemes on triangular meshes*, Journal of Computational Physics, v150 (1999), pp.97-127.

[42] I. Iliev; G. Mellema; U. Pen; H. Merz; P. Shapiro; M. Alvarez, Simulating cosmic reionization at large scales - I. The geometry of reionization, MNRAS, 369, (2006), 1625.

[43] P. Jamkhedkar, H. Zhan, and L.Z. Fang, Intermittent behavior of cosmic mass field revealed by QSO's Lyα forests, ApJ, 543, (2000), L1

[44] G. Jiang and D.-P. Peng, *Weighted ENO schemes for Hamilton-Jacobi equations*, SIAM Journal on Scientific Computing, v21 (2000), pp.2126-2143.

[45] G. Jiang and C.-W. Shu, *Efficient implementation of weighted ENO schemes*, Journal of Computational Physics, v126 (1996), pp.202-228.

[46] G. Jiang and C.-C. Wu, *A high order WENO finite difference scheme for the equations of ideal magnetohydrodynamics*, Journal of Computational Physics, v150 (1999), pp.561-594.

[47] B. Jones, The origin of scaling in the galaxy distribution, MNRAS, 307, (1999), 376

[48] B. Kim, P.He, J. Pando, L.L. Feng and L. Z. Fang, The velocity field of baryonic gas in the universe, ApJ., 625, 599, (2006)

[49] A. Kogut et al. Wilkinson Microwave Anisotropy Probe (WMAP) First Year Observations: TE Polarization. Astrophys.J.Suppl. 148 (2003) 161.

[50] S. Liang and H. Chen, *Numerical simulation of underwater blast-wave focusing using a high-order scheme*, AIAA Journal, v37 (1999), pp.1010-1013.

[51] R. Liska and B. Wendroff, *Composite schemes for conservation laws*, SIAM Journal on Numerical Analysis, v35 (1998), pp.2250-2271.

[52] R. Liska and B. Wendroff, *Two-dimensional shallow water equations by composite schemes*, Int. J. Numer. Meth. Fl., v30 (1999), pp.461-479.

[53] J.R. Liu, L.Z. Fang, L.L. Feng, H.G. Bi, The reionization history in the lognormal model, ApJ, (2004) in press

[54] J.R. Liu; H.G. Bi; L.L. Feng; L.Z. Fang, Is the Cosmic Ultraviolet Background Fluctuating at Redshift $z = 6$?, ApJL, 645, (2006), 1.

[55] J.R. Liu; J.M. Qiu; L.L. Feng; C.-W. Shu; L.Z. Fang, 21 cm Signals from Early Ionizing Sources, ApJ, 663, (2007), 1.

[56] J.R. Liu; L.Z. Fang, Non-Gaussianity of the Cosmic Baryon Fluid: Log-Poisson Hierarchy Model, ApJ, in press (2008)

[57] A. Lazarian; D. Pogosyan, Studying Turbulence Using Doppler-broadened Lines: Velocity Coordinate Spectrum, ApJ, 652, (2006), 1348.

[58] X.-D. Liu, S. Osher and T. Chan, *Weighted essentially non-oscillatory schemes*, Journal of Computational Physics, v115 (1994), pp.200-212.

[59] P. Madau; F. Haardt; M. Rees, Radiative Transfer in a Clumpy Universe. III. The Nature of Cosmological Ionizing Sources ApJ, 514, (1999), 648.

[60] J.M. Marti and E. Muller, *Numerical hydrodynamics in special relativity*, Living Rev. Relativity, 6, (2003), 7. Online Article: cited November 1, 2004, http://www.livingreviews.org/lrr-2003-7

[61] A. Maselli; A. Ferrara; B. Ciardi, CRASH: a radiative transfer scheme, MNRAS, 345, (2003), 379.

[62] S. Matarrese, & R. Mohayaee, The growth of structure in the intergalactic medium, MNRAS, 329, (2002), 37

[63] G. Mellema; I. Iliev; M. Alvarez; P. Shapiro, C2-ray: A new method for photon-conserving transport of ionizing radiation, New Astronomy, 11, (2006), 374

[64] J. Miralda-Escude, Reionization of the Intergalactic Medium and the Damping Wing of the Gunn-Peterson Trough, ApJ, 501, (1998), 15.

[65] P. Montarnal and C.-W. Shu, *Real gas computation using an energy relaxation method and high order WENO schemes*, Journal of Computational Physics, v148 (1999), pp.59-80.

[66] J.S. Mulchaey, *X-ray properties of groups of galaxies*, Annual Review of Astronomy and Astrophysics, v38 (2000), pp.289-335.

[67] T. Nakamoto; M. Umemura; H. Susa, The effects of radiative transfer on the reionization of an inhomogeneous universe, MNRAS, 321, (2001), 593.

[68] J. Navarro, and S. White, Simulations of dissipative galaxy formation in hierarchically clustering universes-2. Dynamics of the baryonic component in galactic haloes, MNRAS, 267, (1994), 401

[69] M. Omang, S. Borve, and J. Trulsen, Numerical simulation of shock-vortex interactions using regularized smoothed particle hydrodynamics, Computational Fluid Dynamics Journal, 12(2):32, (2003).

[70] J.P. Ostriker and E.T. Vishniac, Generation of microwave background fluctuations from nonlinear perturbations at the ERA of galaxy formation, Astrophysical Journal, v306 (1986), pp.L51.

[71] J. Owen, J. Villumsen, P. Shapiro, H. Martel, Adaptive Smoothed Particle Hydrodynamics: Methodology. II. ApJS, 116, (1998), 155

[72] J. Pando; L. Feng; P. Jamkhedkar; W. Zheng; D. Kirkman; D. Tytler; L.Z. Fang, Non-Gaussian Features of Transmitted Flux of QSOs' Ly Absorption: Intermittent Exponent, ApJ, 574, (2002), 575.

[73] F. Pearce, H. Couchman, Hydra: a parallel adaptive grid code, New Astronomy, 2, (1977), 411

[74] U-L. Pen, A High-Resolution Adaptive Moving Mesh Hydrodynamic Algorithm, ApJS, 115, (1998), 19.

[75] J.M. Qiu; L.L. Feng; C.-W. Shu; L.Z. Fang, A WENO algorithm of the t emperature and ionization profiles around a point source, New Astronomy, 12, (2006), 398.

[76] J.M. Qiu; J.R. Liu; C.-W. Shu; L.Z. Fang, A WENO Algorithm for the Growth of Ionized Regions at the Reionization Epoch, New Astronomy, in press (2008)

[77] M. Rauch, *The lyman alpha forest in the spectra of quasistellar objects*, Annual Review of Astronomy and Astrophysics, v36 (1998), pp.267-316.

[78] A. Razoumov; D. Scott, Three-dimensional numerical cosmological radiative transfer in an inhomogeneous medium, MNRAS, 309, (1999), 287.

[79] A. Razoumov; M. Norman; T. Abel; D. Scott, Cosmological Hydrogen Reionization with Three-dimensional Radiative Transfer, ApJ, 572 (2002), 695.

[80] E. Rijkhorst; T. Plewa; A. Dubey; G. Mellema, Hybrid characteristics: 3D radiative transfer for parallel adaptive mesh refinement hydrodynamics, A&A, 452, (2006), 907.

[81] D. Ryu, J.P. Ostriker, H. Kang and R. Cen, *A cosmological hydrodynamic code based on the total variation diminishing scheme*, Astrophysical Journal, v414 (1993), pp.1-19.

[82] S. F. Shandarin and Ya. B. Zeldovich, The large-scale structure of the universe: Turbulence, intermittency, structures in a self-gravitating medium, Rev. Mod. Phys. 61, 185, (1989), 220.

[83] P. R. Shapiro; M.L. Giroux, Mark L. Cosmological H II regions and the photoionization of the intergalactic medium, ApJ, 321, (1987), 107.

[84] P. Shapiro; I. Iliev; A. Raga, Photoevaporation of cosmological minihaloes during reionization, MNRAS, 348, (2004), 753.

[85] P. Shapiro; I. Iliev; M. Alvarez; E. Scannapieco, Relativistic Ionization Fronts, ApJ, 648, (2006), 922

[86] J. Shi, Y.-T. Zhang and C.-W. Shu, *Resolution of high order WENO schemes for complicated flow structures*, Journal of Computational Physics, v186 (2003), pp.690-696.

[87] C.-W. Shu, *Essentially non-oscillatory and weighted essentially non-oscillatory schemes for hyperbolic conservation laws*, in *Advanced Numerical Approximation of Nonlinear Hyperbolic Equations*, B. Cockburn, C. Johnson, C.-W. Shu and E. Tadmor (Editor: A. Quarteroni), Lecture Notes in Mathematics, volume 1697, Springer, 1998, pp.325-432.

[88] C.-W. Shu, *High order ENO and WENO schemes for computational fluid dynamics*, in *High-Order Methods for Computational Physics*, T.J. Barth and H. Deconinck, editors, Lecture Notes in Computational Science and Engineering, volume 9, Springer, 1999, pp.439-582.

[89] C.-W. Shu and S. Osher, *Efficient implementation of essentially non-oscillatory shock capturing schemes*, Journal of Computational Physics, v77 (1988), pp.439-471.

[90] C.-W. Shu and S. Osher, *Efficient implementation of essentially non-oscillatory shock capturing schemes, II*, Journal of Computational Physics, v83 (1989), pp.32-78.

[91] A. Sokasian; T. Abel; L. Hernquist, Simulating reionization in numerical cosmology, New Astronomy, 6, (2001), 359.

[92] M. Steinmetz, GRAPESPH: cosmological smoothed particle hydrodynamics simulations with the special-purpose hardware GRAPE, MNRAS, 278, (1996), 1005.

[93] V. Springel, N. Yoshida, S. White, GADGET: a code for collisionless and gasdynamical cosmological simulations New Astronomy, 6, (2001) 79

[94] V. Springel and L. Hernquist, Cosmological smoothed particle hydrodynamics simulations: a hybrid multiphase model for star formation, MNRAS, 339, (2003), 289.

[95] R. Sunyaev; M. Norman; G. Bryan, On the Detectability of Turbulence and Bulk Flows in X-ray Clusters, AstL. 29, (2003), 783.

[96] H. Susa, Smoothed Particle Hydrodynamics Coupled with Radiation Transfer PASJ, 58, (2006), 45.

[97] P. Tozzi; P. Madau; A. Meiksin; M. Rees, Radio Signatures of H I at High Redshift: Mapping the End of the "Dark Ages" ApJ, 528, (2000), 597.

[98] M.S. Turner, *The case for Omega(M)=0.33 +/- 0.035*, Astrophysical Journal, v576 (2002), pp.L101-L104.

[99] T. Walker, G. Steigma, D.N. Schramm, K.A. Olive and H.S. Kang, *Primordial nucleosynthesis redux*, Astrophysical Journal, v376 (1991), pp.51-69.

[100] M. Warren, J. Salmon, A portable parallel particle program, Computer Physics Communications, 87, (1995), 266.

[101] D. Whalen; M. Norman, A Multistep Algorithm for the Radiation Hydrodynamical Transport of Cosmological Ionization Fronts and Ionized Flows, ApJS, 162, (2006), 281.

[102] R. White; R. Becker; X. Fan; M. Strauss, Probing the Ionization State of the Universe at z¿6, AJ, 126, (2003), 1.

[103] S. Wyithe, and A. Loeb, Was the Universe Reionized by Massive Population-III Stars? ApJ, 588, (2003), 69.

[104] J. Yang, S. Yang, Y. Chen and C. Hsu, *Implicit weighted ENO schemes for the three-dimensional incompressible Navier-Stokes equations*, Journal of Computational Physics, v146 (1998), pp.464-487.

[105] Ya. B. Zel'dovich and R.A. Sunyaev, The Interaction of Matter and Radiation in a Hot-Model Universe, ApSS, v4 (1969), p.301.

[106] H. Zhan, P. Jamkhedkar, and L.Z. Fang, 2001, The local power spectrum and correlation hierarchy of the cosmic mass field, ApJ. 555, (2001), 58.

[107] Y.-T. Zhang, J. Shi, C.-W. Shu and Y. Zhou, *Numerical viscosity and resolution of high-order weighted essentially nonoscillatory Schemes for compressible flows with high Reynolds numbers*, Physical Review E, v68 (2003), article number 046709, pp.1-16.

[108] Zheng, W., et al., A Study of the Reionization History of Intergalactic Helium with FUSE and the Very Large Telescope, ApJ, 605, (2004), 631.

4 Publications (2005 - 2008)

Refereed journals

1. Distributions of baryon fraction on large scales in the universe, P. He, L.L. Feng and L.Z. Fang, *Astrophys. J.*, **623**, 601, (2005)

   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¿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.

2. The velocity field of baryonic gas in the universe, B. Kim, P.He, J. Pando, L.L. Feng and L. Z. Fang, *Astrophys. J.*, **625**, 599, (2005)

   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., $P(\Delta v) = (1r^y)F(\Delta v/r^y)$. 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} 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.

3. A parameter-free statistical measurement of halos with power spectra, P. He, L.L. Feng and L.Z. Fang, *Astrophys. J.*, **628**, 14, (2005)

   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.

4. Power spectrum and intermittency of Lymanα transmitted flux of QSO HE2347-4342, P. Jamkhedkar, L.L. Feng, W. Zheng and L.Z. Fang, *Astrophys. J.*, **633**, 52, (2005)

   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^{-1}Mpc. 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.

5. Low-redshift cosmic baryon fluid on large scales and She-Levueque's universal scaling, P. He, J.R. Liu, L.L. Feng, C.W. Shu and L.Z. Fang, *Phys. Rev. Lett.*, **96**, 051302, (2006)

   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 r edshift 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.

6. X-ray emission of baryonic gas in the universe: luminosity-temperature relationship and soft band background, T.J. Zhang, J.R. Liu, L.L. Feng, P. He and L.Z. Fang, *Astrophys. J.*, **642**, 625, (2006)

   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 $L_x - \sigma$ distributions are significantly scattered. If we describe

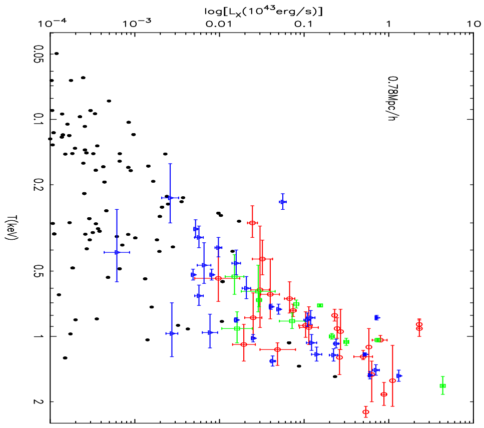

Figure 4.1: X-ray luminosity L_x vs. temperature T for simulation (black) at redshift $z = 0$ with the DWT decomposition on scales 0.78 h^{-1} Mpc. Three sets of observed data are shown by square, circle and triangle.

the relationships by power laws $L_x \propto T^{\alpha_{LT}}$ and $L_x \propto \sigma^{\alpha_{LV}}$, we find $\alpha_{LT} > 2.5$ and $\alpha_{LV} > 2.1$. 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 $\rho_{\rm dm} < 50\bar{\rho}_{\rm dm}$. The region of $\rho_{\rm dm} > 50\bar{\rho}_{\rm dm}$ 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.

7. Cross-correlation between WMAP and 2MASS: non-Gaussianity induced by SZ effect, L. Cao, Y.Q. Chu and L.Z. Fang, *Mon. Not. R. Astr. Soc.*, **369**, 645, (2006)

   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.

8. Is the cosmic UV background fluctuating at redshift $z \simeq 6$? J.R. Liu, H.G Bi, L.L. Feng and L.Z. Fang, *Astrophys. J. Lett.* **645**, L1, (2006)

   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.

9. A unified fitting of HI and HeII Lyα transmitted flux of QSO HE2347 with ΛCDM hydrodynamic simulations, J.R. Liu, P. Jamkhedkar, W. Zheng, L.L. Feng, and L. Z. Fang, *Astrophys. J.*, **645**, 861, (2006)

   Using cosmological hydrodynamic simulations of the LCDM model, we present a comparison between the simulation sample and real data sample of HI and HeII Lyα 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 Lyα transmitted flux. It includes: 1.) the power spectra of the transmitted flux of HI and HeII can be well fitted on all scales ¿ $0.28h^{-1}$ Mpc for H, and ¿ $1.1h^{-1}$ 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 η-scatter is due to the noise in the HeII flux. However, the real data contain more low-η 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

reionization, J.-M. Qiu, C.-W. Shu, L.-L. Feng and L. Z. Fang, *New Astronomy*, **12**, 1, (2006)

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.

11. A WENO algorithm of the temperature and ionization profiles around a point source, J.M. Qiu, L. L. Feng, C.W. Shu and L. Z. Fang, *New Astronomy*, **12**, 398, (2007)

    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.

12. Estimating power spectrum of Sunyaev-Zeldovich effect from the cross-correlation between WMAP and 2MASS, L. Cao, J.R. Liu, and L.Z. Fang, *Astrophys. J.*, **661**, 641, (2007)

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 σ_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, (2007)

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.

14. Lyα Leaks in the Absorption Spectra of High Redshift QSOs, J.R Liu, H.G. Bi & L.Z. Fang, *Astrophys. J. Lett.*, **671**, L89, (2007)

    Spectra of high redshift QSOs show deep Gunn-Peterson absorptions on the blue sides of the Lya emissions lines. They can be decomposed into components called Lya leaks, defined to be emissive regions in complementary to otherwise zero-fluxed absorption gaps. Just like Lya absorption forests at low redshifts, Lya 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 ΛCDM c osmology. In this model, Ly α leaks are mainly due to low density voids. It supports the early studies that the IGM at $z \simeq 6$ would still be in a highly ionized state with neutral hydrogen fraction $\simeq 10^{-4}$. Measurements of $n(W, z)$ at $z > 6$ would be effective to probe the reionization of the IGM.

15. A WENO algorithm for the growth of ionized regions at the reionization epoch, J. M. Qiu, C.W. Shu, J.R. Liu ans L.Z. Fang, *New Astronomy* **13**, 1, (2008)

    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 $c(t_c^i + t_c^j)$, t_c^i 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.

16. Non-Gaussianity of the Cosmic Baryon Fluid: Log-Poisson Hierarchy Model, J.R. Liu and L. Z. Fang, *Astrophys. J.*, **672**, 11, (2008)

    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: β for the intermittency and γ 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 β 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.

17. Lyα Leaks and Reionization,.L. Feng, H.G. Bi, J.R. Liu, and L.Z. Fang, MNRAS, **383**, 1459, (2008)

    Lyα absorption spectra of QSOs at redshifts $z \simeq 6$ 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_H, both of which are less contaminated by instrumental resolution and noise. It is found that the distribution of W and W_H 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 $z \simeq 5 - 6.5$. Similar statistics would also be applicable to the reionization of He II at $z \simeq 3$

18. DWT Analysis of the 2-degree Field Galaxy Redshift Survey, Y.-C. Cai,

J. Pan, L.L. Feng and L.Z. Fang, *ChJAA*, **8**, 159, (2008)

The power spectrum of the two-degree Field Galaxy Redshift Survey (2dFGRS) sample is estimated with the discrete wavelet transform (DWT) method. The DWT power spectra within $0.04 < k < 2.3h\text{Mpc}^{-1}$ are measured for three volume-limited samples defined in connective absolute magnitude bins $-19 \sim -18$, $-20 \sim -19$ and $-21 \sim -20$. We show that the DWT power spectrum can effectively distinguish ΛCDM models of $\sigma_8 = 0.84$ and $\sigma_8 = 0.74$. We adopt maximum likelihood method to perform three-parameter fitting with bias parameter b, pairwise velocity dispersion σ_{pv} and redshift distortion parameter $\beta = \Omega_m^{0.6}/b$ to the measured DWT power spectrum. Fitting results denotes that in a $\sigma_8 = 0.84$ universe the best fitted Ω_m given by the three samples are consistent in the range $0.28 \sim 0.36$, and the best fitted σ_{pv} are 398^{+35}_{-27}, 475^{+37}_{-29} and 550 ± 20km/s for the three samples, respectively. However in the model of $\sigma_8 = 0.74$, our three samples give very different values of Ω_m. We repeat the fitting by using empirical formula of redshift distortion. The result of the model of low σ_8 is still poor, especially, one of the best value σ_{pv} is as large as 10^3km/s. The power spectrum of 2dFGRS seems in disfavor of models with low amplitude of density fluctuations.

19. Scaling relation between Sunyaev-Zel'dovich effect and X-ray luminosity and scale-free evolution of cosmic baryon field, Q. Yan, H.Y. Wan, T.J. Zhang, J.R. Liu, L.L. Feng and L.Z. Fang, *New Astronomy*, in press, (2008)

    It has been revealed recently that, in the scale free range, i.e. from the scale of the onset of nonlinear evolution to the scale of dissipation, the velocity and mass density fields of cosmic baryon fluid are extremely well described by the self-similar log-Poisson hierarchy. As a consequence of this evolution, the relations among various physical quantities of cosmic baryon fluid should be scale invariant, if the physical quantities are measured in cells on scales larger than the dissipation scale, regardless the baryon fluid is in virialized dark halo, or in previrialized state. We examine this property with the relation between the Compton parameter of the thermal Sunyaev-Zel'dovich effect, $y(r)$, and X-ray luminosity, $L_{\rm X}(r)$, where r being the scale of regions in which y and $L_{\rm X}$ are measured. According to the self-similar hierarchical scenario of nonlinear evolution, one should expect that 1.) in the $y(r)$-$L_x(r)$ relation, $y(r) = 10^{A(r)}[L_{\rm X}(r)]^{\alpha(r)}$, the coefficients $A(r)$ and $\alpha(r)$ are scale-invariant; 2.) The relation $y(r) = 10^{A(r)}[L_{\rm X}(r)]^{\alpha(r)}$ given by cells containing collapsed objects is also available for cells without collapsed objects, only if r is larger than the dissipation scale. These two predictions are well established with a scale decomposition analysis of observed data, and a comparison of observed $y(r)$-$L_x(r)$ relation with hydrodynamic simulation samples. The implication of this result on the characteristic scales of non-gravitational heating is also addressed.

Book Chapters and Proceedings

1. Intergalactic medium in the LCDM universe from cosmological simulations, L.L. Feng, P. He, L.Z. Fang, C.W. Shu and M.P. Zhang, *J. of Korean Astr. Soc.*, **38**, 129, (2005)

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) (2005)

3. The history of reionization, L. Z. Fang, *J. of Korean Phys. Soc.*, **49**, 697, (2006)

4. The DWT power spectrum of the two-degree field galaxy redshift survey, Y.C. Cai, J. Pan, Y.H. Zhao, L.L. Feng and L.Z. Fang, *Relativistic Astrophysics* eds. C.L. Bianco and S.-S. Xue, the AIP Conference Proceedings, **966**, 87, (2007)

5. Twenty one cm signals from ionized and heated regions around first stars, L.Z. Fang, *Relativistic Astrophysics* eds. C.L. Bianco and S.-S. Xue, the AIP Conference Proceedings, **966**, 95, (2007)

6. Intermittency of cosmic baryon fluid, L.Z. Fang, *Relativistic Astrophysics* eds. D.S. Lee, W.L. Lee and S.-S. Xue, the AIP Conference Proceedings, in press (2008)

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

4. Invited talk: Einstein, Social responsibility of physicists and human rights in China, APS March meeting, March 22, 2005, Los Angeles.

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
8. Invited talk: Scaling in Cosmology, Institute of Physics, Academia Sinica, Taipei, May 30, 2007
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
14. Colloquium: Studying cosmic baryon fluid with cosmological hydrodynamic simulation, NY university at Stony Brook, Feb 20, 2008
15. Colloquium: Studying cosmic baryon fluid with hydrodynamic simulation, Institute of Physics, Academia Sinica, Taipei, May 27, 2008
16. Invited talk: Intermittency of cosmic baryon fluid, 5th Italian-Sino workshop on relativistic astrophysics, May 29, 2008
17. Public talk: 21 cm signals from early universe, DongHwa University, HuaLien, June 2, 2008