Cosmic Structure Formation at Low and High Redshifts

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The currently standard theory of cosmic structure formation posits that the present-day clumpy appearance of the universe developed through gravitational amplification of the matter density fluctuations that are generated in the very early universe. The energy content of the universe and the basic statistics of the initial density field have been determined with a reasonable accuracy from recent observations of the cosmic microwave background, large-scale structure, and distant supernovae. It has become possible to make accurate predictions from the standard model. Cosmology is now at the stage where we can rigourously test the model against various observations of large- and small-scale structure. We review the latest observations and the recent progress in the theory of structure formation at low and high redshifts. Two promising methods to probe large-scale matter distribution are introduced and the future prospects are discussed. Results from state-of-the-art cosmological simulations are also presented.

§1. Introduction

Observations of extragalactic objects suggest that the universe is approximately homogeneous and isotropic at large scales. The almost perfectly isotropic feature in the cosmic background radiation temperature also manifests that the universe was homogeneous and isotropic, while a variety of clumpy structures are seen in the local universe, such as galaxies and galaxy clusters. One also finds, for instance in the catalogues of galaxy redshift surveys, that there are some patterns or prominent “structures” which extend over tens of mega-parsecs (see Fig. 1). Recent observations of high-redshift galaxies revealed that large-scale structure already existed at $z = 4 – 6$, when the age of the Universe was just one tenth of the present age.\textsuperscript{1,2)} Apparently the universe has undergone a rapid transition from a smooth initial state to the clumpy state as we see today, but details remain largely unknown. Understanding the origin and evolution of the structure of the universe is hence a major goal in modern cosmology.

The so-called standard theory of structure formation posits that the present-day clumpy appearance of the universe developed through gravitational amplification of the initial matter density fluctuations together with other physical processes. This basic picture is now supported by an array of observations, including the measurement of the cosmic microwave background anisotropies by the WMAP satellite.\textsuperscript{3)} The WMAP observation also confirmed that the density fluctuations in the early universe arise from adiabatic perturbations whose statistics are described by a Gaussian field,\textsuperscript{4)} as predicted by popular inflationary theories. The cosmological parameters that describes the dynamics of the universe as a whole are now known to a good

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accuracy. Given these bases, and aided by detailed computer simulations, theoretical models are now able to make accurate predictions for a variety of properties from galaxy clustering to gravitational lensing statistics.

Over the past two decades, cosmological models based on cold dark matter (CDM) have been the most successful, and a variant of the CDM model that invokes dark energy has emerged as the current leading model. While there are still some unsolved issues and possible conﬂictions with observations, the model is now accepted as providing the basic framework of cosmic structure formation.

Fig. 1. The large-scale structure in the local universe. From Gott et al. (2003)

In this paper, we review recent progress and future prospects in the study of structure formation in the universe. Since a number of excellent articles and reviews are available on large-scale structure as probed by galaxy redshift surveys, we refrain from covering the topic. Instead, we introduce two observational probes that enable to map large-scale structure in the distribution of dark matter and that of the intergalactic medium. Large-scale scale structure at high redshift has been recently discovered and has attracted much attention. Observational issues on the “primeval” structure will be extensively reviewed in the contribution of Okamura in this volume. Along with these latest observations, we present the results from state-of-the-art numerical simulations of various kinds.
§2. Probing large-scale structure of the universe

The distribution of galaxies in the sky has been often used for studies on large-scale structure.\(^8\),\(^9\) Prominent clustering features were already found in the projected galaxy distribution in Lick Catalogue compiled in 60’s.\(^8\) Galaxy redshift surveys added the third dimension, in terms of redshift, by which one can make a full three-dimensional map of the galaxy distribution.\(^10\) Statistical methods such as two-point correlation functions\(^11\),\(^12\) and power spectrum are most often used to quantify the clustering of galaxies, against which predictions from theoretical models are tested. Nowadays these basic statistics are used to determine cosmological parameters. The two current-generation redshift surveys, the 2-degree Field Survey\(^13\) and the Sloan Digital Sky Survey,\(^14\) are providing unprecedented data in both quality and quantity. Important global quantities and statistics such as luminosity functions, clustering strengths, and also the properties of galaxy clusters, can be obtained with a tremendous precision from the large set of data.

The best motivation for the CDM model is its predictive power on the formation of large-scale structure. However, extremely large-scale structure (> 100 Mpc) is rarely formed in the CDM model. Fig. 1 shows the largest scale structure found in the CfA survey and that in the Sloan survey.\(^6\) The CfA “Great Wall” extends \(\sim 200\) Mpc and the Sloan great wall extends nearly twice longer. Existence of such largest-scale structure may challenge the standard model, if commonly discovered in the local and distant universe.\(^7\) It remains to be seen whether or not even larger scale structure exists in our universe.

While the distribution of galaxies provides an overall picture of matter distribution, there is always a complex issue of “bias”. One usually assumes that galaxies are fair tracer of underlying mass, introducing a convenient factor called bias. Estimating bias with respect to the underlying mass is non-trivial, however. Bias could (or rather, is likely to) depend on length scale and time, and could be nonlinear with respect to the local density. Hence it would be ideal if one can directly map the matter distribution. It can indeed be done by means of gravitational lensing observations. In the next section, we review the recent progress in observations of gravitational lensing and also its future prospects.

There is a new, recently proposed way to probe the baryonic matter distribution in the local universe. High-level ions of heavy elements such as carbon, nitrogen and oxygen in the hot intergalactic medium (IGM) emit photons typically in soft-Xray bands. It is expected that next generation X-ray missions can detect these emission lines. Since a large fraction of baryons is thought to be in such warm/hot phases at the present epoch, future soft-Xray missions may reveal the location of ‘missing baryons’. Using the redshift of individual metal lines, it will be possible to map the distribution of the hot IGM in the near future. Probing the distribution of dark matter and the diffuse baryonic matter, together with the galaxy distribution, should provide invaluable informations on the process of structure formation.
Gravitational lensing provides a unique, powerful method to map the distribution of dark matter. Weak-lensing technique exploits the deformation of background galaxies’ shapes to map the mass distribution in and around large-scale structure. A number of weak-lensing surveys have been already carried out and larger-area surveys are being conducted. Statistics of the matter distribution can be used to determine the cosmological parameters. Indeed, the next generation weak-lensing surveys are expected to provide the most precise measurements of the matter power spectrum. It has recently been proved to be feasible to search for clusters of galaxies directly as density enhancements using weak gravitational lensing. A great advantage of weak lensing is that a constructed sample is not biased toward luminous systems which optical or X-ray selected catalogs suffer from.

Fig. 2 shows the weak lensing mass map obtained by the Subaru Suprime33
GTO survey. Fourteen high peaks with $S/N > 4$ are found, among which 11 peaks are confirmed to be galaxy clusters by follow-up optical observations. Seven peaks are newly discovered clusters, demonstrating the ability of finding clusters (massive halos) by weak lensing surveys. In principle, the halo number counts can be directly comparable with accurate model predictions based on the results from $N$-body simulations, and thus can be used to put strong constraints on cosmological parameters. While the number of samples in the Subaru GTO survey is still poor, the halo number count is consistent with the prediction from the $\Lambda$CDM model.

Detailed studies of weak-lensing cluster surveys using large $N$-body simulations have been recently carried out. Fig. 3 shows the predicted number counts of halos with $S/N > \nu$, where $\nu$ is the peak height in the convergence map, by two representative observational facilities, a space telescope and a ground-based one. The ability of weak-lensing surveys to locate massive dark halos is promising. Even with the current generation telescopes, the halo detection efficiency is comparable to that of X-ray cluster search. Future lensing surveys of clusters exploiting a space telescope will detect $\sim 50 - 100$ halos with $S/N > 4$. With this high signal-to-noise ratio, contamination by noise is expected to be small.

Fig. 3. (Left) The gray scale with contour lines shows the $S/N$ value for weak lensing halo detection as a function of halo mass and redshift. (Right) Predicted number counts of peaks which can be detected by a ground-based telescope and by a space telescope. From Hamana, Takada & Yoshida (2004)

Future weak-lensing surveys will also allow very accurate determination of cosmological parameters through the lensing power spectrum. Fig. 4 shows the expected accuracy of the power spectrum measurement by the SNAP mission. It is clearly seen that models with different cosmological parameters can be distinguished. It is also worth noting that the lensing power spectrum is a sensitive probe of the equation of state of dark energy.
Fig. 4. Prospects for the measurement of the weak-lensing power spectrum with future surveys. The thick lines are the lensing power spectra for the indicated three cosmological models. The boxes are estimated 1σ errors for the SNAP wide survey. The thin line is the linear power spectrum. From Refregier (2003).[^19]

2.2. Missing baryons in the local universe

The distribution of baryonic matter in the universe remains one of the puzzling issues. At the present epoch, the total amount of baryons inferred from observations of HI absorption, gas and stars in galaxies, and X-ray emission from hot gas in galaxy clusters is far smaller than that predicted by nucleosynthesis calculations[^20],[^21] and that determined by measurements of the cosmic microwave background radiation[^3]. Hence, it is now widely believed that about 30-50% of the baryons in the local universe is in yet unknown, dark state.

Numerical simulations of structure formation consistently suggest that a large fraction of such missing baryon is in the warm/hot state with temperature $10^5 - 10^7$ K[^23],[^24]. In those simulations, such component is found around massive clusters and in filamentary structure. Fig. 5 shows the result from a recent large cosmological simulation[^25]. The warm/hot component is clearly seen as filamentary structures bridging cluster (high density) regions. The gas is mostly shock-heated to a temperature of $\sim 10^5 - 10^7$ K during large scale structure formation, and this relatively low temperature of the gas makes it hard to detect its thermal emission by conventional X-ray observations.

A variety of observational approaches have been suggested to study the warm/hot
The distribution of gas (top), the warm/hot component with $10^6 < T < 10^7$ K (middle), and the gas that has a two-temperature structure with $T_e < 0.5 T_i$ (bottom) in a slab of $100 \times 100 \times 20 (h^{-1} \text{Mpc})^3$. From Yoshida, Furlanetto & Hernquist (2005)\(^{25}\)

intergalactic medium (WHIM) using either hydrogen or various metal ions. With respect to the latter possibility, there have been several tentative claims that the WHIM has been detected locally in absorption\(^{26}\) and in emission.\(^{27}\) Nicastro et al.\(^{28}\) recently estimated the total amount of baryons in the warm/hot phase using O\text{vii} absorbers in the spectra of two blazers. Fig. 6 shows the observed number of O\text{vii} absorbers per unit redshift, compared with the result from a numerical simulation for the $\Lambda$CDM model.\(^{29}\) They claim that the inferred total mass-density in the warm absorber is consistent with the theoretical prediction, i.e., roughly half of baryons in the local universe is in the WHIM.

Detecting the WHIM in quasar absorption lines (or those of other X-ray sources)
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Fig. 7. Estimated baryon mass fraction which can be detected through oxygen emission lines. Contributions of baryons with $T < 10^6\text{K}$, $10^6 < T < 10^7\text{K}$, $T > 10^7\text{K}$ are shown separately. From Yoshikawa et al. (2004)

is always hampered by the fact that observations are limited along line-of-sights toward such objects. Yoshikawa et al. (2004)

have proposed using Ovii/Oviii emission lines to probe the WHIM in detail with high spectral resolution X-ray detectors. From planned configuration and sensitivity of the Diffuse Intergalactic Oxygen Surveyor (DIOS) mission, they estimate that about half of the WHIM (in mass) can be detected via oxygen line emission. With DIOS, it is possible not only to detect a large fraction of the WHIM but also to map the distribution in the local universe because redshift of individual lines can be used to determine the distance to the WHIM. Fig. 7 shows the ability of the proposed DIOS mission. A substantial fraction of the hot IGM ($T > 10^6 \text{K}$) can be probed. These estimates, however, rely on some crucial assumptions on the IGM metallicity and the relative population of ionization levels of oxygen.

Since the population of different ionization stages and the excitation rate of each ion are primarily determined by electron impact, it is important to model appropriately the evolution of electron temperature in the WHIM. In the particular simulation shown in Fig. 5, the evolution of electron/ion temperatures and the relaxation processes are explicitly followed. It is clearly seen that a bulk of the WHIM has a well-developed two temperature structure where the electron temperature is substantially smaller than the ion temperature. The two-temperature structure of the WHIM has many important implications. A factor of two systematic shift in temperature, typical of the offsets between $\bar{T}$ and $T_e$ near shocks, can lead to significant over/under-estimates of the ion abundances. Interestingly, when the deviation of the electron temperature is taken into account, the emissivity of Ovii lines around massive clusters increases. (25) This is because the gas in outskirts of clusters is re-
cently shock-heated, having a low electron temperature of $\sim$ a few million degrees, where the O\textsuperscript{vii} emissivity has a peak. The intensity increase (relative to a single temperature model) can be locally by an order of magnitude, making it promising to probe the outer-part of clusters via oxygen emission lines.\textsuperscript{25)}

Fig. 8. Distribution of the WHIM in the local universe simulation of Yoshikawa et al. (2004)\textsuperscript{31)}

The color scale shows the intensity in soft-Xray band (0.5-2 keV). Several large clusters are indicated in the map.

In the local Universe, there are some prominent large-scale structure such as Virgo cluster and Pisces-Perseus supercluster region. Thus there may be a large amount of WHIM also in our local Universe.\textsuperscript{30),31)} Fig. 8 shows the distribution of the WHIM in the simulated local universe. The simulation is a ‘constrained realization’ of the local universe starting from a smoothed linear density field which matches that derived from the IRAS 1.2 Jy galaxy survey.\textsuperscript{32),33)} Large-scale structures are seen at approximately right positions with right sizes. These nearby massive clusters will be a primary target of the next generation soft-Xray mission. It will be a land-marking work in observational cosmology if a large fraction of the missing baryon (which should then be the majority of baryons in the local universe) is finally discovered in our ‘neighbour’.
§3. Hierarchical structure formation and the cosmological first objects

In this section, we first describe generic features of structure formation in CDM models. We then discuss the characteristic mass scale of the cosmological first objects, showing the results from simple analytic models and those from a detailed numerical simulation.

The primordial density fluctuations predicted by popular inflation models have simple characteristics. They are described by a random Gaussian field, and have a nearly scale-invariant power spectrum \( P(k) \propto k^n \) with \( n \sim 1 \). Subsequent growth of perturbations in the radiation-dominated and then in the matter-dominated era results in a modified power spectrum, but the final shape is still simple and monotonic in CDM models; the power spectrum has a feature that it has progressively larger amplitudes on smaller length scales. Hence structure formation is expected to proceed in a “bottom-up” manner, with smaller objects forming earlier.

It is useful to work with a properly defined mass variance to obtain the essence of non-linear evolution and collapse in the CDM model. The mass variance is defined as

\[
\sigma^2(M) = \frac{1}{2\pi^2} \int P(k) W^2(kR) k^2 dk,
\]

(3.1)

where the top-hat window function is given by \( W(x) = 3(\sin(x)/x^3 - \cos(x)/x^2) \). We also define the threshold over-density for collapse at \( z \) as

\[
\delta_{\text{crit}}(z) = \frac{1.686}{D(z)},
\]

(3.2)

where \( D(z) \) is the linear growth factor to \( z \). Fig. 9 show the variance and the collapse threshold at \( z = 0, 5, 20 \). At \( z = 20 \), the mass of the halos which correspond to 3-\( \sigma \)
fluctuation is just about $10^6 M_\odot$. As shown later in §3.1, this mass scale coincides with the characteristic mass of the first objects in which the primordial gas can cool and condense.

It is worth noting that the mass variance is sensitive to the initial power spectrum. In warm dark matter models in which the power spectrum has an exponential cut-off at the particle free-streaming scale,\(^{34}\) or in models in which the primordial power spectrum has a ‘running’ feature,\(^{35,36}\) the corresponding mass variance at small mass scales is reduced.\(^{37,38}\) In such models, early structure formation is effectively delayed, and hence nonlinear objects form later than in the CDM model. Thus the formation epoch of the first objects and hence that of cosmic reionization have a direct link to the nature of dark matter and the primordial density fluctuations.

There are excellent reviews available on the study of the formation of the first stars and reionization of the universe,\(^{39-41}\) so we do not attempt to cover a broad range of the topics here. Rather, we focus on a few important issues in the study of early structure formation.

Fig. 10. The projected gas distribution at $z = 17$ in a cubic volume of $600 h^{-1} \text{kpc}$ on a side. The cooled dense gas clouds appear as bright spots at the intersections of the filamentary structures. From Yoshida et al. (2003).\(^{50}\)
3.1. **Formation of the first cosmological objects**

Observations of distant quasars revealed that the intergalactic medium was highly ionized at $z < 6$. High resolution spectroscopic studies of quasars at $z > 6$ showed a significant increase in Ly-$\alpha$ absorption with the first detection of the Gunn-Peterson trough.$^{42,43}$ These results indicated that cosmic reionization completed at $z \sim 6 - 7$. However, results from the WMAP satellite have challenged this scenario by suggesting that the IGM is significantly ionized much earlier than inferred from the quasar observations.$^{44}$ The Thomson optical depth determined from the temperature-polarization correlation is $\tau \sim 0.17$, suggesting that a large fraction of the IGM was ionized at $z \sim 17$. While there is still a substantial uncertainty in this measurement, it is clear that the first cosmic structure emerged very early on.

Planned observational programs will exploit future instruments such as *JWST* and *ALMA* to probe the physical processes which shaped the high-redshift Universe. Among the relevant scientific issues are the star formation rate at high-redshift, the epoch of reionization, and the fate of high-redshift systems. The statistical properties of early baryonic objects are of direct relevance to understanding the significance of the first stars to these phenomena. In this context, the key theoretical questions can be summarized as *when and where did a large population of the first stars form? and how and when did the Universe make the transition from primordial to “ordinary” star formation?*

The study of the cooling of primordial gas in the early universe and the origin of the first baryonic objects has a long history.$^{45-47}$ (see also the contribution by Haiman in this volume). Recent numerical studies of the formation of primordial gas clouds and the first stars indicate that this process likely began as early as $z \approx 30$ in the CDM model.$^{48-50}$ In these simulations, dense, cold clouds of self-gravitating molecular gas develop in the inner regions of small halos and contract into proto-stellar objects with masses in the range $\approx 100 - 1000 M_\odot$. Fig. 10 shows the projected gas distribution in a cosmological simulation that includes hydrodynamics and detailed chemistry.$^{50}$ The primordial star-forming gas clouds are found at the nodes of filaments, resembling galaxy clusters and filamentary structure, although being much smaller in mass and size. (This manifest the hierarchical nature of structure in the CDM universe.) The simulation evolved the non-equilibrium rate equations for 9 chemical species of primordial composition and include the relevant gas heating and cooling in a self-consistent manner. From a large sample of dark halos, necessary conditions under which the first baryonic objects form are identified.

Fig. 11 shows the molecular fraction $f_{\text{H}_2}$ against the virial temperature for halos. The solid line is an analytical estimate of the $\text{H}_2$ fraction needed to cool the gas, which we compute a là Tegmark et al.$^{51}$ In Fig. 11, halos appear to be clearly separated into two populations; those in which the gas has cooled (top-right), and the others (bottom-left). The analytic estimate indeed agrees very well with the distribution of gas in the $f_{\text{H}_2} - T$ plane. However, it can be also seen that not only the $\text{H}_2$ fraction determine whether or not the gas in halos can cool. In Fig. 12, the mass evolution

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$^{*}$ http://ngst.gsfc.nasa.gov/

$^{**}$ http://www.nro.nao.ac.jp/lmsa/
Fig. 11. The mass weighted mean $H_2$ fraction versus virial temperature for the halos that host gas clouds (filled circles) and for those that do not (open circles) at $z = 17$. The solid curve is the $H_2$ fraction needed to cool the gas at a given temperature and the dashed line is the asymptotic $H_2$ fraction.

Fig. 12. The mass evolution of the halos that host gas clouds at $z=17$ (left) and those that do not (right).

is plotted for a subset of halos that host gas clouds (top-left panel) and of another subset of halos that do not host gas clouds (top-right panel). In the top-left panel, filled circles indicate when they host gas clouds. The figures show a clear difference between the two subgroups in their mass evolution. Most of the halos in the top-left panel experience a gradual mass increase since the time their masses exceeded $M_{cr}$, whereas those plotted in the top-right panel have grown rapidly after $z \sim 20$. It
appears that the gas in halos that accrete mass rapidly (primarily due to mergers) is unable to cool efficiently. Therefore, “minimum collapse mass” models are a poor characterization of primordial gas cooling and gas cloud formation, because these processes are significantly affected by the dynamics of gravitational collapse. This suggests that it is important to take into account the details of halo formation history in the CDM model.

3.2. Feedback from the first objects

The birth and death of the first generation of stars have important implications for the thermal state and chemical properties of the intergalactic medium in the early universe. The initially neutral, chemically pristine gas was reionized by ultraviolet photons emitted from the first stars, but also enriched with heavy elements when these stars ended their lives as energetic supernovae. The importance of supernova explosions, for instance, can be easily appreciated by noting that only light elements were produced during the nucleosynthesis phase in the early universe. Chemical elements heavier than lithium are thus thought to be produced exclusively through stellar nucleosynthesis, and they must have been expelled by supernovae to account for various observations of high-redshift systems. The destruction of star-forming regions by radiation from the first stars and/or by supernova explosions is also of considerable cosmological interest. If the primordial gas cloud and the halo gas are completely blown away by a single supernova explosion, star-formation is quenched for a long time in the same region.

3.2.1. Radiative feedback

The first feedback effect we consider is radiation from the first stars. Cosmic reionization by stellar sources proceeds first by the formation of individual H\textsuperscript{II} regions around radiation sources (stars/galaxies), and then by percolation of the growing H\textsuperscript{II} bubbles.\textsuperscript{52)–54)} The shape and the extension of the individual H\textsuperscript{II} regions critically determine the global topology of the ionized regions in a cosmological volume at different epochs during reionization.

Studies on the formation of H\textsuperscript{II} regions in dense gas clouds date back to the seminal work by Strömgren.\textsuperscript{55)} Since then the structure of H\textsuperscript{II} regions and the interaction with the surrounding medium have been extensively studied.\textsuperscript{56), 57)} Recently, two groups carried out radiation hydrodynamics simulations of ionization front propagation around the first stars.\textsuperscript{58), 59)} The simulations start from a realistic initial density profile for primordial star-forming clouds and include gravitational forces exerted by the host dark matter halo. These two conditions make the evolution different from that of present-day local H\textsuperscript{II} regions.

Fig. 13 shows the radial profiles of various quantities in an early H\textsuperscript{II} region.\textsuperscript{58)} The star-forming region is defined as a spherical dense molecular gas cloud with a power-law density profile within a dark matter halo, and a single massive Population III star with $M^\ast = 200 M_\odot$ is embedded at the center. The formation of the H\textsuperscript{II} region is characterized by initial slow expansion of weak D-type ionization front near the center, followed by rapid propagation of R-type front throughout the outer gas envelope. The transition between the two front types is indeed a critical condition for
the complete ionization of halos of cosmological interest. In small mass ($< 10^6 M_\odot$) halos, the transition takes place within a few $10^5$ years, yielding high escape fractions ($> 80\%$) of both ionizing and photodissociating photons. Fig. 14 shows the escape fractions for a large range of halo mass. The gas in small mass halos is effectively evacuated by a supersonic shock (see Fig. 15), with the mean density within the halo decreasing to $\lesssim 1 \text{cm}^{-3}$ in a few million years. In larger mass ($> 10^7 M_\odot$) halos, on the other hand, the ionization front remains to be of D-type over the lifetime of the massive star, the H\textsc{ii} region is confined well inside the virial radius, and the resulting escape fractions are essentially zero.

Fig. 13. Structure of an H\textsc{ii} region around a massive Population III star inside a minihalo. Radial profiles of (a) hydrogen number density, (b) gas temperature, (c) ratio of radiation force to gravitational force, (d) ionization fraction, (e) molecular hydrogen fraction, and (f) radial velocity, at indicated output times are shown. From Kitayama, Yoshida, Susa & Umemura (2004)\textsuperscript{18}
Fig. 14. Escape fractions of ionizing photons (> 13.6eV) and the Lyman-Werner photons (11.2-13.6eV) as a function of host halo mass.

Fig. 15. Evolution of baryon fraction within virial radius in our fiducial runs. The stellar radiation evacuates nearly all the gas is within a few to ten million years.\textsuperscript{58)
The strong dependence of the photon escape fraction indicates that only the first stars formed in small mass halos ($\lesssim 10^6 M_\odot$) can contribute to IGM ionization. It is also interesting that the critical mass for the escape of the Lyman-Werner photons, which dissociate hydrogen molecules, is slightly larger than that of ionizing photons. Nearly all the Lyman-Werner photons can escape from halos with $M \sim 10^6 M_\odot$. A strong negative feedback is expected to be caused by these systems.

3.2.2. Mechanical feedback

Recent theoretical studies on the formation of primordial stars consistently suggest that the first stars were rather massive,\(^{(48), (49), (60)}\) with an important exception that those formed via filamentary collapse may be as small as $\sim 1 M_\odot$.\(^{(61)}\) If the first stars are indeed as massive as $\sim 200 M_\odot$, they end their lives as energetic SNe via the pair-instability mechanism,\(^{(62)–64)}\) releasing a total energy of up to $\sim 10^{53}$ ergs. Such energetic explosions in the early universe are thought to be violently destructive: they expel the ambient gas out of the gravitational potential well of small-mass dark matter halos, causing an almost complete evacuation.\(^{(66), (67)}\) Since the massive stars process a substantial fraction of their mass into heavy elements, early SN explosions may provide an efficient mechanism to pollute the surrounding intergalactic medium.\(^{(68)}\)

The physics of astrophysical blastwaves has been extensively studied since early 70’s.\(^{(69)–71)}\) On a cosmological background, Ikeuchi\(^{(69)}\) suggested energetic explosions in the early universe as a large-scale star-formation and galaxy formation mechanism. Population III supernova explosions in the early universe were also considered as a trigger of star-formation.\(^{(72)}\) Modern numerical simulations have been carried out by two groups.\(^{(66), (67)}\) It has been shown that the expelled gas by supernovae falls back to the dark halo potential well after about the system’s free-fall time. While these previous works consistently showed the destructive aspect of early supernova explosions, they employed idealized or simplified initial conditions and hence the precise effect remains uncertain. The density and density profile around the supernova sites are of particular importance because the efficiency of cooling of SNRs is critically determined by the density inside the blastwave.

As shown in the previous section, for ‘mini-halos’ with mass $\sim 10^6 M_\odot$, I-fronts quickly expand to a radius of over 1 kpc and the halo gas is effectively evacuated. Interestingly, the final gas distribution is very different for cases with small ($\sim 10^6 M_\odot$) and large ($\sim 10^7 M_\odot$) mass halos. The radial profiles of density, temperature and velocity at the death of the central star should provide appropriate initial conditions for the studies of subsequent SN feedback.

Kitayama and Yoshida\(^{(73)}\) carried out hydrodynamic simulations of radiative supernovae remnants at $z \sim 20$, starting the simulations from the resulting density profiles in the first HII regions. Fig. 16 shows the evolution of the radial profiles of various quantities around the supernova site. The blastwave quickly propagates over the halo’s virial radius, leading to complete evacuation of the gas even with the input energy of $10^{51}$ erg. A large fraction of the remnant’s thermal energy is lost in $10^5 – 10^7$ yr by line cooling, whereas, for larger explosion energies, the remnant cools mainly via inverse Compton scattering. In the early universe, the inverse Compton
Fig. 16. Evolution of the early SNR in the case of $E_{\text{SN}} = 10^{51}$ erg, $M_{\text{host}} = 3.2 \times 10^5 M_\odot$, and $M_e = 200 M_\odot$; (a) hydrogen density, (b) gas temperature, and (c) outward velocity at $t = 0$ (dotted lines), $3 \times 10^5$ (dashed) and $10^7$ yr (solid), where $t$ denotes the time elapsed since the end of the free expansion stage. The vertical dotted line indicates the virial radius of the host halo. From Kitayama and Yoshida (2005).

The situation drastically changes if there were no I-front expansion prior to the SN explosion. Such cases may be realized when ionizing photons do not break out from the very central region and a ultra-compact HII region is formed. If the initial density profile of the run shown in Fig. 16 is modified to a pure power-law with $\rho \propto r^{-2}$, assuming that the density profile has not been significantly modified by radiation, the cooling time of the inner-most shell gets extremely small and the ejected energy is rapidly lost during the free-expansion stage. Accordingly the blastwave

$q = \frac{Q}{m c^2}$
stalls in the dense environment and the halo gas in the outer envelope will not be undisturbed. This is the case even if the ejected SN energy is much greater than the binding energy for baryons within the virial radius. This clearly shows the importance of setting-up appropriate initial configurations in quantifying the degree of SN feedback and that simple analytic estimates based on explosion energy to binding energy ratio are unreliable.

Fig. 17. Destruction efficiency of the first supernovae. Halos blown away even in the absence of initial I-front expansion are marked by triangles, those blown away only in the presence of I-front initial expansion by circles, and those not blown away by crosses. Dotted and dashed lines show the binding energy of the gas for a given \( M_h \) and 300 times the same quantity, respectively.

Fig. 17 summarizes the results from a series of calculations of Kitayama & Yoshida.\(^{73}\) A simple criterion, \( E_{SN} > E_{bi} \), where \( E_{bi} \) is the gravitational binding energy, is often used to determine the destruction efficiency. However, whether or not the halo gas is effectively blow-away is determined not only by the host halo mass (which gives an estimate of \( E_{bi} \)), but also by a complex interplay of hydrodynamics and radiative processes. SNRs in dense environments are highly radiative and thus a large fraction of the explosion energy can be quickly radiated away. An immediate implication from the result is that, in order for the processed metals to be transported out of the halo and distributed to the IGM, I-front propagation and pre-evacuation of the gas must precede the supernova explosion. This roughly limits the mass of host halos from which metals can be ejected to \( < 10^6 M_\odot \) for explosion energy \( \lesssim 10^{53} \) erg.

As has been often discussed in the literature,\(^{67,68}\) the feedback effects from the
first stars tend to quench further star-formation in the same place. Although metal-enrichment by the first supernovae could greatly enhance the gas cooling efficiency, which would then change the mode of star-formation to that dominated by low-mass stars,\(^{78}\) the onset of this ‘second-generation’ stars may be delayed particularly in low-mass halos. Hence early star-formation is self-regulating; if the first stars are massive, only one period of star-formation is possible for a small halo and its descendants within a Hubble time then. The sharp decline in the efficiency of both feedback effects at \(M_{\text{halo}} > 10^7 M_\odot\) (see Fig. 14, 17) indicates that the global cosmic star formation activity increases only after such larger halos start forming. An important question remains, however. Without metal-enrichment, gas cooling efficiency is still limited even though hydrogen atomic line cooling becomes effective in halos with \(T_{\text{vir}} > 10^4\) K. Oh & Haiman\(^{74}\) argue that H\(_2\) molecules are needed as main coolants for the primordial gas to further fragments in a dense gaseous disk in large halos. If the formation of H\(_2\) is strongly suppressed by a soft-UV background, star-formation does not take place, or the first black holes may be formed in low-spin halos.\(^{75}\) Further studies on star-formation in such large halos are clearly needed.

Fig. 18. The large-scale parent simulation at \(z = 20\) showing the highest density peak within a portion of \(100\ h^{-1}\)Mpc on a side (left panel). The earliest object formed in this peak region at \(z = 49\) is shown on the right. The bottom-right panel shows the projected gas density field in a cubic volume of \(100\) pc on a side centered at the primordial gas cloud. From Gao et al. (2005)\(^{77}\)

3.3. The earliest object in a \(\Lambda CDM\) universe

Numerical simulations and analytic models of the first cosmic structure to date mostly addressed the formation of the first objects within a hypothetical volume
or in a statistical sense. As has been discussed in the previous sections, halos with $T_{\text{vir}} \sim 1000-2000$ K are usually thought to be hosts of the first stars; those collapsing at $z \sim 20$ from 3-$\sigma$ density peaks typically correspond to these. However, nonlinear growth of the high density peaks and the formation of the first objects could occur in a significantly biased manner. They could also cause large-scale feedback effects. Hence any statistical argument based on averaged quantities in a ‘mean’ density universe may miss important aspects of early structure formation. An interesting question in this context is, when and where did the very first star form?

An analytic estimate based on the Extended Press-Schechter theory tells that the highest redshift object in the observable volume of an observer at $z=0$ should be one formed from an 8-$\sigma$ fluctuation at $z \sim 48$. In the CDM model, the earliest structures are expected to be such extremely rare objects, and thus it is very unlikely to be found in usual cosmological simulations employing a small volume. Recently Gao et al. carried out a series of very high resolution re-simulations to locate one of the earliest objects in a cosmological volume. The multi-level re-simulations were set-up and carried out in the following manner. A very massive halo is identified in a large simulation box of $(0.68\text{Gpc})^3$ volume at $z = 0$. This cluster and its immediate surroundings are re-simulated with a higher mass resolution. Then a halo merging tree is constructed and the progenitor, which contributes most in mass, is identified at some earlier epoch. The progenitor is again re-simulated at a higher mass resolution using a zoom-in technique. At each refinement level, small length-scale perturbations are added to the particle displacement field in order to realize a proper initial condition for the given CDM power spectrum. In their highest resolution simulation, the gas particle mass is $0.34h^{-1}M_\odot$ and that of dark matter is $2.2h^{-1}M_\odot$. Fig. 18 shows a portion of the parent simulation and the earliest object in the highest resolution simulation. Significant small-scale clustering is seen already at $z = 49$. A halo with mass $3 \times 10^5M_\odot$ is formed at the center, and the gas within it has reached the characteristic state of the primordial molecular gas cloud with temperature $T \sim 200$ K and particle number density $n_H \sim 10^4 \text{cm}^{-3}$. The Jeans mass for these values is $M_{\text{Jeans}} \sim 3000M_\odot$, and the cloud mass has already exceeded $M_{\text{Jeans}}$ at $z = 49$. The gas cloud is thus expected to collapse, although it occurs slowly.

Since these earliest objects are extremely rare, the net feedback effect from them is limited to its surroundings. For instance, even if a very massive star is formed in the gas cloud, the Lyman-Werner photons would just escape from the region and absorbed by relic intergalactic H$_2$. Within the same halo, the subsequent evolution of the gas and the formation of the second-generation objects may be significantly disturbed by them, via various effects as discussed in the previous sections. In particular, if very massive stars are formed in these objects and end their lives as energetic supernova, they expel heavy elements such as carbon and oxygen, hence dramatically changing the gas cooling efficiency. In such cases, the gas is first expelled from the host halo, which has just a mass of $3 \times 10^5M_\odot$ at $z=49$, and eventually falls back when the halo grows and becomes more massive. This fall-back time scale is crudely estimated to be at least of the order of the system’s dynamical time, which is $\sim 10$ Myrs at $z = 49$. This could be much delayed because the
expelled gas is initially moving outward with a velocity greater than the halo’s virial velocity (see the bottom panel in Fig. 16). It is found that the host halo mass of the ‘earliest’ object in the simulation increases to $M = 2 \times 10^6 h^{-1} M_\odot$ by $z = 35$. The corresponding virial temperature is just above $10^4$K, at which the gas can cool by hydrogen atomic transitions. Hence the formation of the second-generation object, the first proto-galaxy, is expected to occur in the same region only at $z \lesssim 35$. This epoch is still earlier than the collapse epoch of $10^6 M_\odot$ halos from 3-$\sigma$ density peaks. If stars are formed efficiently in these pre-galactic objects, they will be the brightest sources at the epoch and may contribute significantly to reionization.

### 3.4. Prospects for observations

We have discussed the physics of early structure formation and presented recent development in theoretical studies. We would like to close this chapter by mentioning future observations. The nature of the sources of the first light and the origin of heavy elements have not been determined yet, but the prospects for observationally revealing these issues in the near future appear bright. The ongoing operation of WMAP will yield a more precise value for the total optical depth to reionization. In the longer term, post-WMAP CMB polarization experiments such as Planck will probe the reionization history. Detection of small-angular scale CMB fluctuations and, particularly, the second-order polarization anisotropies on arcminute scales can place strong constraint on the details of reionization. Near-infrared observations of afterglows from high-redshift gamma-ray bursts can also be used to probe the reionization history at possibly $z > 10$. Mapping the morphological evolution of reionization may be possible by observations of redshifted 21cm emission in particular by the Square Kilometer Array and LOFAR. Analyses of these various high-precision data promise to provide a more complete picture of cosmic reionization and possibly the matter density distribution in the early Universe over a wide range of scales and its relationship to the formation of stars and galaxies. The precise measurement of the near-IR cosmic background radiation will constrain the total amount of light from early generation stars. Ultimately, direct imaging and spectroscopic observations of high redshift star clusters by the James Webb Space Telescope will probe the evolution of stellar populations up to $z \sim 10 - 15$.

Measurements of the relative abundances of various heavy elements in metal-poor stars should provide valuable information on the formation history of our Milky Way as well as the chemical evolution of the universe. Interestingly, a strong argument against very massive ($> 140 M_\odot$) stars comes from the observed abundance pattern of C-rich, extremely Fe-deficient stars. It remains to be seen whether or not such stars are truly second generation stars and their elemental abundances should precisely reflect the metal-yield from the first supernovae. Observations of a large number of extremely metal-poor stars will construct better statistics and improve constraints on any models for the early chemical evolution. Understanding the origin of the first heavy elements in the universe and the nature of the sources that are responsible for cosmic reionization will require the concerted use of data from these broad classes of observations.
§4. Non-standard models: alternative to CDM?

The cold dark matter model has become the leading theoretical framework for the formation of structure in the Universe. While a broad range of recent observations provided strong support for the $\Lambda$CDM model in which cold dark matter and dark energy dominate, the lack of experimental evidence of such dark components and the fact that the physical origin and nature of them remain unknown make the model still speculative. Thus it appears to be worth exploring alternative scenarios and consider structure formation in non-standard models.

Modified Newtonian Dynamics (MOND) has been often proposed as an alternative to dark matter in many different contexts, from the internal dynamics of galaxies\(^{102}\) to large-scale structure.\(^{103}\) While so far a number of arguments against MOND have been made based on various observations,\(^{104}–^{106}\) MOND appears to die hard. Moreover, it has had its own intrinsic problem that the corresponding relativistic theory does not exist. Bekenstein\(^{107}\) recently made the first attempt to construct a relativistic MOND theory. It will be of considerable interest if the formation and evolution of structure in a MONDian universe can be addressed in a fully self-consistent manner.

More recently, several specific attempts were made to construct self-consistent cosmological models including the deviation from Newton’s law on cosmological scales. For instance, Dvali, Gabadadze and Porrati\(^{108}\) proposed a scenario to explain the accelerating universe as a result of leaking gravity to extra dimension in the context of braneworld model. According to this model, the accelerating universe can be accounted for without dark energy component, but due to the modification of Newton’s law of gravity on cosmological scales. Other models which suggest deviations from Newton gravity on cosmological scales include a ghost condensation model\(^{109}\) and scalar-tensor theories.\(^{110}\) A few attempts have been made to constrain deviations from the inverse-square Newtonian law of gravity on cosmological scales.\(^{111}–^{113}\) Shirata et al.\(^{112}\) consider specifically deviation that is described by an additional Yukawa-like term. They derived constraints on the amplitude and the length scale by comparing the predicted matter power spectra in this non-Newtonian model and the galaxy-galaxy power spectrum from the SDSS, on the assumption that galaxies are linearly biased tracer of the underlying mass. As shown by Shirata et al., large-scale structure as probed by galaxy clustering or gravitational lensing observations may provide a unique tool to test the Newtonian gravity at cosmological length scales $\gg 1\text{Mpc}$.

Another context in which CDM models are often claimed to be in trouble is the ‘fine’ structure of dark matter halos, typically that of galactic-size halos. Despite a great amount of works devoted to the issue of “core or cusp” in the past several years in both theory and observations, there hasn’t been any clear resolution nor even a consensus on whether or not the problem is real rather than apparent. From theoretical interest, relatively minor modifications to the CDM model have been proposed. Such models invoke additional properties of dark matter particles\(^{116}–^{118}\) or slight change in the primordial power spectrum.\(^{119}\) These models, however, either have their own difficulties or lack strong motivation from fundamental physics, and
thus they are now thought to be unattractive alternatives.

The angular resolution of observations (and other technical details) of rotation curve measurements are often ascribed as the source of the discrepancy. However, even the most recent high resolution H-α observations still show some convincing cases where the central density profiles are rather flattened, being in conflict with the CDM prediction.\textsuperscript{114} Interpreting the measured rotation curves is another complex issue. It has been suggested that reconstructing the density profile of a triaxial dark halo from rotation curve measurements is nontrivial. For some viewing angles the density profiles can appear much shallower than the actual profile.\textsuperscript{115} It seems that the key point in this issue is to conduct a fair comparison between observation and simulations. Detailed studies on galaxy and gas kinematics in CDM halos will eventually provide a resolution to the discrepancy.

§5. Conclusions

We would like to summarize this article by making remarks to the following three important questions in cosmology:

1. \textit{How are luminous matter and dark matter distributed in the universe, and what is the origin of bias?}
   
   Current generation galaxy redshift surveys are providing a detailed picture of galaxy distribution in the local universe. It will soon become possible to probe the distribution of dark matter by weak gravitational lensing observations, and that of diffuse baryons using X-ray telescopes. By making a complete ‘map’ of all these components, we will discover \textit{differences} in their distributions, and will obtain a comprehensive knowledge on the process of structure formation.

2. \textit{How and when did the first stars and the first galaxies form?}
   
   Promisingly, a number of observational plans are underway, to detect CMB polarizations, metal-poor relic stars, signatures in infrared background, metals in high-z Lyman-α forests, and faint light from very high-z galaxies. Understanding the origin of the first heavy elements in the universe and the nature of the sources that are responsible for cosmic reionization will require the concerted use of data from these broad classes of observations. To this end, theoretical (as opposed to phenomenological) astrophysics can play a role.

3. \textit{We all bet for the ΛCDM model?}
   
   While there appear to be some confictions with observations and possible theoretical difficulties such as the ‘unnatural’ value of Λ, it may be fair to say that there is yet no strong case against the Λ + Cold Dark Matter model. Still the most fundamental issue remains; the physical origin and nature of the dark components. The direct laboratory detection of massive particles would provide the most convincing confirmation of the dark matter paradigm. Strong motivations for the existence of dark energy from fundamental physics must be explored; otherwise worth seeking alternatives perhaps in the theory of gravity.
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