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Cosmology with the intergalactic medium

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Abstract. We discuss a few new results which points out the importance of the intergalactic medium as a diagnostic for the formation and evolution of galaxies in the Universe. We discuss the recent studies to determine the power spectrum of fluctuation from QSO-absorption line studies, and then some feedback processes from early galaxies which influence the intergalactic medium.

Keywords. Cosmology; galaxy evolution; intergalactic medium.

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1. Introduction

The last few years have seen significant developments in the field of the intergalactic medium in the context of structure formation and cosmology in general. The intergalactic medium, which was once thought to be as a mere spectator in the scenario of structure formation is now being seen as an important participant in the whole process. At one end, the intergalactic medium is now thought to fragment and collapse onto structures of various sorts, due to density fluctuation in the Universe at small scales. These structures then, in the hierarchical structure formation models, form bigger structures ultimately leading to galaxies.

At the other end, there is also feedback onto the intergalactic medium from the process of galaxy formation and evolution. The radiation from hot and young stars in galaxies and radiation from QSOs could have reionized the intergalactic medium (IGM) and heated it. The galaxies could also have enriched the IGM, just as the intracluster medium has been enriched. These aspects of the feedback from galaxy formation and evolution have become an interesting topic recently.

2. Structure formation and IGM

Until recently, the IGM used to be thought of as consisting of a diffuse homogeneous medium in which discrete ‘clouds’ of overdense gas were embedded. These discrete clouds, often simplified to be spherical systems, were thought to cause the absorption lines in the spectra of distant QSOs. Understanding the physical nature of these ‘clouds’ posed a lot of problems, mostly because of the simplified manner one thought of them.

Recent numerical simulations have shown a much more elegent way to think of the IGM and to interpret these absorption lines. Also, high resolution spectra from high redshift QSOs have enabled the astronomers to compare some of these ideas with observations to a high accuracy.

Instead of dividing the QSO spectra into discrete lines of various HI column densities, one now thinks of the spectra being caused by a continuously varying density field in the line of sight. Lines with small HI column density, say of order $N_{\rm HI} \lesssim 10^{14.5}$ cm^{-2} comes from regions with overdensities of order $\rho/\bar{\rho} \lesssim 10$ at $z \sim$ 2–5. Most of the gas is only slightly non-linear, and it looks like that effects of shock heating etc influences regions with a small volume filling factor. The behaviour of this mildly overdense gas can be understood from simple considerations of photoionization from the background UV radiation and recombination. These consideration leads to a simple relation between the HI content of the region and the overdensity, or, equivalently, the HI opacity, which can be directly measured, and the overdensity.

Firstly, considering the heating due to photoionization and cooling due to adiabatic expansion and recombination, one can derive the evolution of the temperature of the gas [1]. For a typical background radiation spectrum and for typical reionization histories, it turns out that $T = T_0 (\rho/\bar{\rho})^{\alpha}$, where $4000 \lesssim T_0 \lesssim 10^4$ K and $0.3 \lesssim \alpha \lesssim 0.6$. Secondly, Since the recombination rate is $\propto T^{-0.7}$, the equilibrium HI content is $\propto \rho^2 \Gamma_{\rm HI}/T^{-0.7}$, where $\Gamma_{\rm HI}$ is the photoionization rate. This turns out that,

$$\begin{aligned} &\tau = A(\rho/\bar{\rho})^{\beta} \,, \\ &A \sim 0.8 \Big(\frac{1+z}{4}\Big)^{6} \Big(\frac{\Omega_b h^2}{0.02}\Big)^{2} \Big(\frac{h}{0.65}\Big)^{-1} \Big(\frac{H(z)/H_0}{4.5}\Big)^{-1} \\ &\qquad \times \Big(\frac{\Gamma_{\rm HI}}{10^{-12} s^{-1}}\Big)^{-1} \Big(\frac{T_0}{10^4\, K}\Big)^{-0.7} , \end{aligned} \tag{1}$$

where $\beta \sim 1.6$, A is a parameter to be determined.

Given this relation between the opacity (or lack of flux) and the overdensity, one can recover the underlying density field which causes the absorption features in the QSO spectra. Croft *et al* [2] have recently determined the 1-D line of sight density field from a high resolution spectrum, after determining the value of A from comparison of numerical simulation results with different values of A with the observed spectra. They then converted the 1-D power spectrum to a 3-D power spectrum and compared with the theoretical expectations.

These exercises give the power spectrum upto lengthscales $2\pi/k \sim 700$ km s^{-1}, where it has never been probed earlier. The slope of the power spectrum seems to agree with with inflation+CDM models. Croft *et al* [2] found from a study of 17 QSO spectra that for open CDM models the best fit gives $\Omega_0 \sim 0.5 \pm 0.1$ and for flat model, $\Omega_0 \sim 0.35 \pm 0.1$. Although these values are to be treated as being tentative, they already show the importance of studying the IGM in the context of structure formation in the Universe. One big advantage of getting the power spectrum from IGM is that one need not worry about the 'bias factor' that crops up when one recovers the power spectrum from galaxy surveys.

Therefore, one now looks at the IGM as fragmenting under the influence of the primordial density fluctuation at high redshift, and which has a web-like structure, with filaments, sheets interconnected through vortices. Simulations show that gas in the IGM collapses onto these structures (filaments/sheets), which are transient as the gas flows towards the vortices with a timescale of a Hubble time.

The lines with HI column densities much larger than 10^{15} cm^{-2}, however, need to be treated with caution. These absorption lines are usually accompanied by metal lines, which suggest some amount of chemical evolution. They are definitely caused by in-situ star formation in these galaxies or proto-galaxies, and the evolution in time of the metallicity and line density have been modeled. We will instead focus on the enrichment of the lower column density lines below.

3. Feedback from structure formation

As far as the feedback processes from galaxy formation on the IGM is concerned, one important question is what keeps the IGM ionized at high redshift. The clues to this question is to be found in the spectrum and amplitude of the ionizing background radiation, if photoionization is the cause of reionization. The UV background radiation at high redshift has been determined to some accuracy by the so-called Proximity effect from the study of Lyman-α forest clouds. The intensity at the Lyman break (912 Å) has been found to be of order $J = 10^{-21\pm0.3}$ erg cm^{-2} s^{-1} sr^{-1} Hz^{-1}. It is supposed to peak around $z \sim 2$–3 although the evolution at higher redshift is not yet conclusive. One, therefore, has to look for sources which can give rise to such a radiation with this evolution in time.

In addition to the amplitude, one also has some ideas about the spectrum of this radiation. The difference between absorption due to HI and that due to other species indicates the difference between the abundance of HI and other different ionization species of other elements, say, helium. This in turn indicates the ratio of the intensity of the ionizing radiation at frequencies corresponding to threshold of ionization of the respective species. For example, the comparison of absorption due to HI and HeII, the absorption due to which has been detected in the last few years, is suggestive of the difference in the intensity at 912 Å and 304 Å. In other words, one has an idea of the spectrum from these observations although the accuracy is limited by the fact that there are a number of steps in the process and many assumptions involved. For example, we have found that observations constrain the ratio of the intensity at these wavelengths, S_L can be between 16 and 650 at $z \sim 2.5$ [3].

The spectrum is a diagnostic of the sources of the ionizing background. For example, if QSOs are the primary cause of the radiation, then the spectrum is expected to be harder than if star-forming galaxies are the dominant sources (a hard spectrum means a small value for S_L). Recently, using semi-analytical calculations of galaxy formation and evolution, which uses some prescription for star formation and includes the effect of dust obscuration in early galaxies, and which uses the hierarchical structure formation models, it has been found that galaxies could not have been a dominant source of the ionizing radiation [4]. The constraints used are (1) observed evolution of the luminosity density in different bands, UV, optical, near and far-infrared (2) evolution of HI content of the Universe as deduced from the observations of damped Lyman-α systems and (3) evolution of metallicity in the Universe, again deduced from damped Lyman-α systems. It was found that galaxies can become as dominant as QSOs at very low redshifts but QSOs are dominant by a large factor at higher redshifts.

This exercise was, however, done within a redshift range of $1 < z \lesssim 4$, although one knows from QSO spectra from higher redshift that the Universe has been reionized even before this. What could have ionized the Universe then and kept it ionized before $z \sim 4$ is yet to be determined and it is a topic of interest now.

Another feedback process is that of enriching the IGM by the early galaxies. Nearby starburst galaxies have been observed to have galactic winds, powered by supernovae from a frenzy of star formation. The same mechanism is supposed to be at work in enriching the intracluster medium, the hot gas in clusters. It is therefore possible that early galaxies had enriched the IGM through galactic winds. This is very interesting because the IGM has been recently found to be enriched at $z \sim 3$.

The metallicity of Lyman-α absorption systems with large HI column densities mentioned above are definitely due to in-situ star formation. The cause of the enrichment of the Lyman-α forest systems, with $N_{\rm HI} \gtrsim 10^{14.5}$ cm^{-2} is yet to be determined. In the numerical simulations, these lines usually come from the gas near the vortices in the IGM-web. The question is whether the enrichment is due to in-situ star formation, or due to a more pervading enrichment of the IGM at some earlier epoch. Cowie *et al* and others found in the last couple of years that the metallicity of systems with $N_{\rm HI} \gtrsim 10^{14.5}$ cm^{-2} is almost independent of the HI column density and is of order $10^{-2.5}$ solar. One should keep in mind that the determination of the metallicity depends on the knowledge of the ionizing background radiation spectrum. Recently Lu *et al* [5] claimed that they could not detect any CIV lines in systems with lower column densities and the upper limit to the metallicity is $10^{-3.5}$ for $N_{\rm HI} \lesssim 10^{14}$ cm^{-2}. Cowie and Songaila [6], however, claimed recently that the even these systems are enriched to almost the same level.

If the enrichment has been more pervasive, then one possibility is that it was done by pregalactic objects at very high redshifs, and numerical simulations (Gnedin and Ostriker [7]) show that it is possible to enrich the IGM to the observed level, and they also show that the metallicity will be small in systems with small overdensities, that is low HI column density. It is also possible to enrich the IGM with conventional galactic winds form early galaxies at $5 \lesssim z \lesssim 10$ [8,9] in the framework of standard structure formation models.

The detection of heavy elements in IGM raises the question whether or not there is also dust and if dust heating can be become important as compared to the simple photoionization heating. Hot electrons ejected by ionizing background photons impinging on dust grains can heat up the ambient gas. We have done detail calculation for this scenario, with different type of dust and different mixtures, with different ionizing background radiation spectra and found that dust heating can be comparable to and in some cases more important than simple photoionization heating. The temperature of Lyman-α systems, regions overdense by a factor of ~ 10, can be increased by a factor of order two more than in the case of only photoionization. There are some evidences for temperature evolution in redshift in Lyman-α systems although they are not yet conclusive [10].

If there is dust, then in addition to heating the gas, it will also radiate and will distort the background radiation in the infrared region. Although the spectral distortion of the CMBR has been found to be small, we recently found that if the overdense regions are clustered, then the resulting anisotropy is still an order of magnitude smaller than the upper limits observed now but it could be significant for future observations ($\langle \Delta I_d^2 \rangle^{1/2} \langle I_d \rangle \sim 10^{-5}$ at $10''$ scales and at 360 GHz) [11].

Another interesting feedback process is from the mechanical energy input from early quasars if the formation of black holes had been efficient in the past. According to Ensslin *et al* [12], it is possible that such energy input could have raised the pressure of the IGM to a few $\times 10^{-16}$ erg/cc, compared to the usual value of pressure assumed from photoionization heating, of order 10^{-18} erg/cc.

We therefore find that the IGM has become an important diagnostic tool for probing galaxy formation and evolution.

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