The IGM at high redshift and galaxy formation.

Alain Blanchard\textsuperscript{1}, Simon Prunet\textsuperscript{2}

\textsuperscript{1}Observatoire astronomique de Strasbourg, ULP, 11, rue de l’universit\'e, 67 000 Strasbourg, France
\textsuperscript{2}Universit\'e de Paris-Sud, Institut d’Astrophysique Spatiale, Bâtiment 121, F-91405 Orsay Cedex, France

Abstract. The conditions for structure formation which ultimately lead to galaxies request further ingredients behind the simple collapse criteria. The Jean’s criteria and the cooling criteria are those which are currently used. However in such a simple scheme, a fundamental problem occurs in hierarchical pictures, namely the overcooling: the predicted fraction of primordial gas expected to have cooled in the history of structure formation is too large. The solution to this problem is likely to be a substantial re-heating phase. Here, we discussed one possible solution: the warm IGM picture. If the feedback of galaxy formation is able to heat the IGM up to temperatures of the order of $10^5 - 10^6$ K, galaxy formation is inhibited on small mass scale. This leads to an inverse hierarchical picture: most of the large galaxies form at redshifts in the range 3 to 5, while small galaxies form at two different epoch: at an early phase at redshift greater than five and at a late phase, between redshift 3 and 0. Such a scheme may reproduce quite well the amount of HI gas versus redshift.

1 Introduction

The problem of galaxy formation is a central problem of cosmology. Recent progresses, both from the theoretical side and the observational side, have triggered numerous works. The most dramatic changes are probably the ability to have access to direct information at high redshift: the HI gas, the star formation rate, the possible detection of an infrared background originating from early galaxies \textsuperscript{4} as well as the direct spectroscopy of high redshift field galaxies provide a number of observational constraints to which theories can now be confronted. The model we present has a amazing small number of free parameters, and still reproduces quite well several key observational constraints.

2 Recipes for galaxy formation

2.1 The global picture

It is generally believed that structure formation originated accordingly to the gravitational instability picture. Structures which achieved a high contrast
density, namely greater than 200, are called virialized. Properties of clusters of galaxies can actually be used as useful constraints on cosmological scenarios. The dynamics of dark matter seems to be understood well enough that the basic time evolution of the correlation function and the mass function of cosmic structures can be described at any redshift provide that the power spectrum of the primordial fluctuations is known. First attempts to address the question of galaxy formation has met a first important apparent success: it has been suggested that a criteria to differentiate dark halos leading to galaxies from those leading to clusters is the cooling criteria. When gas falls in a potential it is shock-heated (and/or by adiabatic compression) up to the virial temperature allowing the gas to be in hydrostatic equilibrium. Numerical simulations has confirmed that this simple argument provides an accurate estimation of the actual temperature:

\[ T_v = 5 \times 10^5 M_{12}^{2/3} (1 + z) \text{K} \]

where \( M_{12} \) is the total mass in unit of \( 10^{12} M_\odot \) of the object forming at redshift \( z \). The typical size of the halo is:

\[ R_v = \left( \frac{T_v}{10^5 \text{K}} \right)^{1/2} \frac{1}{(1 + z)^{3/2}} 45 h^{-1} \text{kpc} \]

When the gas reaches its virial temperature, it has a characteristic cooling time. Clusters typically represent structures for which the cooling time exceeds the age of the universe, while for galaxies it is much shorter. It is tempting therefore to conclude that the cooling criteria can be used as a criteria for star formation: if the gas is able to cool, it will contract in a runaway fashion, which is can end up only by star formation (as there is not so much cooled gas in the universe). This argument successfully explains the order of magnitude of the luminosity of the brightest galaxies (\( L_* \)).

### 2.2 The overcooling problem

The previous scheme has remained a qualitative picture for a while. However, the need for a more quantitative picture has become clear as the amount of data on distant galaxies has increased: from the number counts of faint galaxies to the recent star formation rate versus redshift. The first basic difficulty one faces on in the simple cooling scheme is the so-called overcooling problem: at high redshift a large fraction of the baryons lies is small potentials with temperatures in the range \( 10^4 - 10^6 \text{K} \) in which cooling is extremely efficient. Consequently, most of the baryons are expected to have been cooled by now. This is in clear contradiction with two basic facts: known stars represent only a small fraction of baryons predicted by nucleosynthesis, typically 10% and most of the baryonic content of clusters is still in the gas phase, while most of them should have been cooled. Both facts suggest that only 10% to 20% of the primordial baryons were actually turn into stars during the cosmic history.
Figure 1: Integrated fraction of gas able to cool at various redshift. The different curves correspond to different values of the bias parameter \( b = 1, 1.25, 1.75, 2 \). The thin lines are for for the standard CDM (\( \Gamma = 0.5 \)) while the thick lines are for \( \Gamma = 0.5 \).

This problem was first pointed out by Blanchard et al. [2] and Cole [3]. A simple estimate of the integrated cooled fraction can be obtained from the mass function of cosmic structures, by noticing that any piece of gas within a halo with \( T_v > 10^4 \)K should have settled in the cooling region at some earlier epoch [2]:

\[
F_c(z) = \frac{1}{\rho} \int_{m_4(z)}^{+\infty} N(m)mdm
\]

where \( m_4(z) \) represents the mass of halos which have a virial temperature of \( 10^4 \)K at redshift \( z \). The amount of total cooled gas at different redshift is presented in figure 1. The reality of this overcooling problem is not easy to test by means of numerical simulations because of resolution limitations. However, Navarro & Steinmetz found that [5] provide a reasonable approximation and therefore quite reasonable to believe that the simple based Press and Schechter argument can be used. Therefore, the solution of the overcooling problem implies that the gas have undergone some substantial reheating. The fact that the x-ray luminosity of clusters does not scale as predicted by the scaling argument provide a further evidence of a complicated baryon history.

2.3 The reheating phase

The existence of a reheating phase of baryons has been advocated in various contexts in galaxy formation scenario. For instance, White and Frenk [10]
argued that the energy input of supernova from the first generation of stars is able to prevent the cooling of the gas that remains confined in galactic scale halos. Blanchard et al. [2] suggested a rather different picture: the first objects which form heat the IGM to a temperature high enough that most of the gas does not fall in most of the forming potentials in which cooling would have been possible otherwise because of the temperature of the gas. This introduces the idea that a key physical quantity controlling galaxy formation is the temperature of the IGM, which could be regulated by galaxy formation.

2.3.1 A self-regulated IGM

The basic equation which governs the temperature of the IGM in a self-regulated picture is:

\[(1 - F_c)\rho_b\Lambda(T(z)) = \epsilon \dot{E}_\ast \frac{1}{\rho} \int_{m_T(z)}^{+\infty} N(m) mdm\]  

(4)

where \(T(z)\) is the temperature of the IGM at redshift \(z\), \(m_T(z)\) is the mass associated to this temperature, \(\dot{E}_\ast\) is the total energy output resulting from star formation (essentially Supernova) and \(\epsilon\) is the energy fraction which is transferred to the IGM and \(\Lambda\) is the cooling function. As the IGM is likely to be photo-ionized at the same time that it undergoes the reheating we used the cooling function of a photoionized gas. The temperature of the IGM versus redshift depends on the value of the efficiency of energy injection to the IGM. The temperature of the IGM is increasing from \(10^4\)K to reach a maximum value between \(10^5\)K and \(10^6\)K at redshift of the order of 3 to 5 depending on the details of the model. Such a high temperature will easily explain the absence of detected Gunn-Peterson decrement, even if most of the baryons lies in the IGM. Explaining the existence of Lyman-\(\alpha\) clouds will be certainly challenging for this scenario: they could not be small halos nor large scale fluctuations in the IGM. A possible explanation might be that they are the extended parts of galactic disks.

3 From baryons to stars

Although this model is relatively simple, there are still a number of free parameters. The power spectrum as well as the primodial nucleosynthesis value have been left free until now. The final important free parameter is the value of \(\epsilon\). \(\epsilon = 1\). means that the energy transfer is 100% efficient for a standard IMF (a higher value could be used, due to a non standard IMF or because of extra energy input). The parameter \(\epsilon\) can be constrained by computing the integrated amount of stars produced. The gas which has been cooled can be compared directly the amount of observed HI gas versus redshift: this is presented on figure 2. The models which are presented are those who explained the present amount of stars. At this stage, there are no free parameters other than the power spectrum. The standard CDM spectrum do not lead to the
Figure 2: Theoretical amount of HI gas predicted in the self-regulated photoionized picture. The different curves correspond to different values of the parameter $\epsilon$ ($\epsilon = 0.125, 0.5, 2$) used for different $\Omega_b$ ($\Omega_b = 0.05, 0.10, 0.20$) for the CDM-like spectrum with $\Gamma = 0.25$.)

right amount of HI versus redshift, while the $\Gamma = 0.25$ fits impressively well the observed distribution. Given the relatively small number of free parameters, this is rather amazing. A further step can be obtained by noticing that the HI gas is likely to be the progenitors of present day stars (or at least of the progenitors of stars in disks). Assuming that the HI gas is transformed in stars but with some delay, we can infer the star formation rate at different redshift and compare it to the one inferred by Madau [6] from the CFRS survey and HDF. This is illustrated by figure 3. Such modeling is rather crude, but is still rather instructive: we found that the rapid decrease of star formation rate between redshift 1 and 0 is expected in the self-regulated photoionized picture. Moreover the amplitude can be well reproduced, provide that star formation from cooled HI is delayed by 2 Gyr. The high redshift star formation rate is not well reproduced: the theoretical model systematically predicted a higher star formation rate. It is fundamental to realize that this is due to the fact the Madau star formation rate integrated from redshift 5 to 0 cannot explain the total amount of present day stars, and therefore either this formation rate has been underestimated or there is an other period of earlier star formation at high redshift (which is not expected in any of the models presented here).

4 Conclusion

One of the strongest problem in the galaxy formation history is the so-called overcooling problem. It is likely that its solution and consequently the galaxy
Figure 3: Star formation rate versus redshift in the warm photo-ionized picture assuming a delay of 2 Gyr. The observational points are from [6].

Formation history is connected to the thermal (and chemical) history of the IGM. We have presented a simple global coherent picture of the stars formation history based on the hypothesis of a self-regulating mechanism. This simple model impressively succeeds in explaining the whole set of present day observational constraints one can set on galaxy formation theory. It is therefore interesting to investigate such a model in more details.

Acknowledgements. We would like to thank the organizers of the 1997 IAP meeting for this exciting meeting, for the wonderful conference dinner and for their patience...

References

[1] Bartlett, J., 1997, astro-ph/9703091
[2] Blanchard, A., Valls-Gabaud, D., Mamon, G., 1990, Proceedings of the XX Rencontres de Moriond in Astrophysics, eds. J.-M. Alimi, A. Blanchard, A. Bouquet, F. Martin de Volny and J. Tran Thanh VAn, Editions Frontieres, p. 403; Blanchard, A., Valls-Gabaud, D., & Mamon, G., 1992, A&A 264, 365
[3] Cole, S, 1991, ApJ 367, 45
[4] Evrard, A.E., astro-ph/9701148
[5] Hamilton, A. J. S., Matthews, A., Kumar, P. LU, E., 1991, ApJ , 374, L1; Peacock, J. A.; Dodds, S. J., 1996, MNRAS 280, 19P
[6] Madau, P., astro-ph/9612157
[7] Navarro & Steinmetz, 1997, ApJ , 478, 13
[8] Press, W. H., & Schechter, P. L. 1974, ApJ , 187, 425
[9] Puget J.-L. et al., 1996, A&A 308, L5
[10] White, S.D.M. & Frenk, C..S., 1991, ApJ 379, 52