PROCEEDINGS OF SCIENCE

Galaxy formation in voids: Photo-evaporation

Matthias Hoeft*
International University Bremen
E-mail: m.hoeft@iu-bremen.de

Gustavo Yepes[1], **Stefan Gottlöber**[2], **Volker Springel**[3]
[1]*Universidad Autonoma de Madrid*
[2]*Astrophysikalisches Institut Potsdam*
[3]*Max-Planck-Institut für Astrophysik, Garching*

The diffuse cosmic UV-background caused by Quasars and massive stars photo-heats the gas in dark matter halos. It can be boiled out when the potential well of the halo is sufficiently shallow. Consequently, a lower mass limit for galaxy formation is set by the UV-background. Standard CDM structure formation models predict a significantly higher number of satellite dwarf galaxies in the Local Group than actually found. We study a similar substructure problem: pure N-body simulations predict a large number of dwarf galaxies in cosmological void regions but only few of them are found. For both the substructure problem of the Local Group and the missing dwarf galaxies in voids photo-heating is a promising mechanism in order to remove the discrepancies. In void regions at $z = 0$ we find that baryons are photo-evaporated in halos with mass below $M_c \sim 6 \times 10^9\, h^{-1}\, M_\odot$. We argue the characteristic mass M_c at a given redshift is set by the ability of a halo to shock-heat infalling gas sufficiently to reach the instable branch of cooling/heating equilibrium at high densities in the gas phase-space diagram. The temperature in the cooling/heating equilibrium varies only slightly but the temperature in accretion shocks is essentially given by the virial temperature of a halo which evolves roughly $\propto (1+z)$ for a given mass. Therefore, the characteristic mass scale M_c is much lower at earlier times. As a consequence those halos which are below M_c at present may have an early epoch of star formation. When the characteristic mass rises above the halo mass no new gas can be added to the star forming gas reservoir, but star formation out of the reservoir is still possible.

Baryons in Dark Matter Halos
5-9 October 2004
Novigrad, Croatia

*Speaker.

PoS(BDMH 2004)094

Introduction

Hierarchical models of structure formation produce in standard cold dark matter cosmologies large underdense regions in the distribution of matter. These regions still contain structural elements and bound halos. Using pure N-body simulations Gottlöber et al. [1] predicted that a typical $\sim 20\,h^{-1}$ Mpc diameter void should contain up to 1000 halos with mass $\sim 10^9\,h^{-1}\,M_\odot$. Each halo should represent a dwarf galaxy if no efficient mechanism is present which suppresses galaxy formation in low-mass halos. Void dwarf galaxies are excellent test objects for basic processes in galaxy formation, since they are rather isolated and galaxy properties therefore are little affected by mergers. Basically two mechanisms can limit star formation in small halos: Photo-evaporation due to the ionizing cosmic UV-background and galactic winds caused by supernovae. The latter do only occur as a consequence of star formation, moreover, recent numerical studies indicate that galactic winds can remove only partly the baryonic content even in small halos. Hence, the cosmic UV-background has to play a crucial role in setting the lower mass limit for galaxy formation.

We study the evolution of several void regions with $\sim 16\,h^{-1}$ Mpc diameter. Here we discuss the results for the characteristic mass scale at which photo-evaporation occurs and the consequences for the stellar halo content. Simulations and results are presented in detail in a forthcoming paper [3].

Simulations

We have carried out 'zoom'-simulations of void regions in a $50\,h^{-1}$ Mpc box. The concordance cosmological model is adopted ($\Omega_M = 0.3, \Omega_\Lambda = 0.7, \Omega_B = 0.045, h = 0.7$). Simulations are carried out with the TreeSPH code GADGET including radiative cooling/heating and a subgrid model for star formation with thermal and kinetic supernovae feedback [2]. Mass refinement in the void region leads to a dark matter mass resolution of $10^6\,h^{-1}\,M_\odot$. Thus the gas mass resolution is $1.8 \times 10^5\,h^{-1}\,M_\odot$. We have deliberately switched off kinetic supernovae feedback in order to isolate the impact of photo-heating.

Photo-evaporated halos

In the presence of a UV-background small halos in the simulations are virtually free of baryons. The characteristic mass at which the baryon fraction $M_{\rm baryon}/M_{\rm tot}$ is half of the cosmic mean amounts to $M_c \sim 6 \times 10^9\,h^{-1}\,M_\odot$ for a standard UV-flux at $z = 0$. From the simulations we derive the evolution of M_C with redshift, see Fig. 1 left panel. It decreases significantly and at $z = 5$ it amounts to $\sim 10^8\,h^{-1}\,M_\odot$. In contrast, void galaxies accrete their mass very slowly, therefore, the dwarf galaxies typically evolves from state above M_c at high redshift to a state below M_C at present. As a consequence gas may be photo-evaporated from dwarf galaxies. However, considering the history of individual halos reveals that gas which is already condensated ($\rho > 1000\,\langle\rho\rangle$, $T < 10^5$ K) is in most galaxies not subject to photo-evaporation, see right panel. Instead at some time only further condensation starts to be suppressed. As a result the baryon fraction decreases. The earlier the suppression begins the lower is the baryon fraction in the end.

To condensate gas it first has to be sufficiently heated by accretion shocks to overcome the pressure barrier of dense gas in the galaxy center. On the basis of this argument we derive a criterion

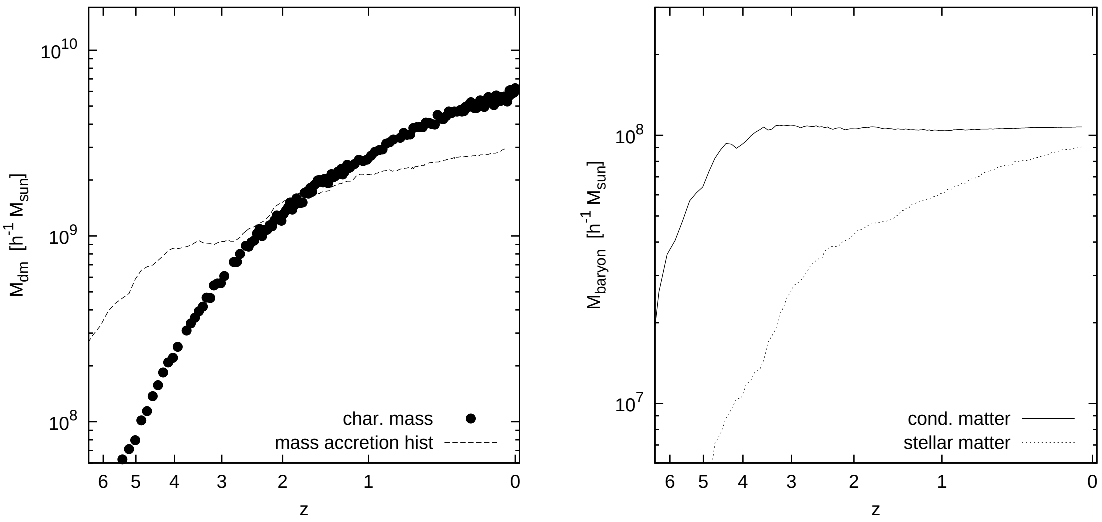

Figure 1: *left panel:* The characteristic mass obtained from a high-resolution simulation (black circles). We determine for a large number of redshifts the mass at which the baryon fraction in a halo is in average half of the cosmic mean. For comparison the mass accretion history of one sample halo is shown (dashed line). *right panel:* Mass accretion history of the condensated baryonic mass and the stellar mass for the sample halo (see left panel). The condensated mass remains constant when the total mass of the halo is below the characteristic mass. In contrast the stellar mass continuously increases; no clear imprint noticeable from the fact that the characteristic mass rises above the total halo mass.

which tells us the minimum halos mass which is necessary to overcome the barrier. Furthermore we derive the evolution of $M_C(z)$ in nice agreement with our measurements in the simulation [3].

Stellar population

Our results indicate that the imprint of photo-ionization onto the stellar population in dwarf galaxies is less direct than previously expected. The condensed gas phase, at least for halos with $M_{\rm tot} \gtrsim 10^9\,h^{-1}\,M_\odot$, is not subject to photo-evaporation. Out oft this reservoir stars can still be formed even if the total mass of a galaxy is below the characteristic mass. In our simulation only the gas of the smallest galaxies is evaporated, this is possibly a numerical artefact.

The halo mass function of dark matter halos shows in both in void and in dense regions a steep slope towards the faint end. We can use our results for evaporation and compute the mass function of the luminous matter only. Now the low-mass behavior changes dramatically: Photo-evaporation causes a flat mass function below $\sim 10^9\,h^{-1}\,M_\odot$. This mass function could be, in principle, observed. Assuming the same baryon content is universal for all halos one would draw the wrong conclusion about a much shallower total mass function in voids.

References

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