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BIMODAL GAS ACCRETION IN THE HORIZON-MARENOSTRUM GALAXY FORMATION SIMULATION

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Abstract. This proceedings summarizes some of the findings of Ocvirk et al. 2008. The physics of diffuse gas accretion and the properties of the cold and hot modes of accretion onto proto-galaxies between z=2 and z=5.4 is investigated using the large cosmological simulation performed with the RAMSES code on the MareNostrum supercomputing facility. Galactic winds, chemical enrichment, UV background heating and radiative cooling are taken into account in this very high resolution simulation. Using *accretion–weighted temperature histograms*, we have measured the transition halo masses characterizing the existence of stabel hot shocks $\mathrm{M_{shock}}$ and filamentary gas accretion $\mathrm{M_{stream}}$.

We find a hot shock transition mass of $\mathrm{M_{shock}} = 10^{11.6}\mathrm{M_\odot}$, with no significant evolution with redshift. Conversely, we find that $\mathrm{M_{stream}}$ increases sharply with z. This is in striking agreement with the analytical predictions of Birnboim & Dekel 2003 and Dekel & Birnboim 2006, *if we correct their metallicity assumptions to those we measure when computing radiative cooling rates*. We therefore find that metal enrichment of the intergalactic medium is a key ingredient in determining the transition mass from cold to hot dominated diffuse gas accretion.

1 Introduction

It is currently accepted that the ΛCDM theory provides a framework with which a large number of observed galaxy properties can be interpreted. This framework is referred to as the "hierarchical scenario of galaxy formation". Most importantly, this framework explains why many of these properties (physical sizes, black hole mass, bulge mass...) are found to correlate simply with galaxy mass. Amidst this apparently simple scaling of galaxy properties with mass, the discovery of a bimodality in the colour distribution of Sloan Digital Sky Survey (SDSS) galaxies Kauffmann et al. 2003 stood unexpected and at odds with the predictions of hierarchical galaxy formation. Indeed, in the simplest flavours of the hierarchical buildup of galaxies, massive ellipticals would still be blue and forming stars at $z = 0$. The fact that observed elliptical galaxies do not obey this fundamental prediction is the origin of the so-called "anti-hierarchical" behaviour of massive red galaxies (Rasera & Teyssier 2006). This observation is further supported by the analysis of spectroscopic data, using star formation history reconstruction methods (Panter et al. 2003, Ocvirk et al. 2006a,b). Since these giant galaxies are in the form of apparently "dead" (i.e. no ongoing star formation) red elliptical galaxies, the quest has been ongoing for several years to find the origin of this halt in the star formation process (also refered to as "star formation quenching").

In this respect, the detailed analysis of diffuse gas accretion around star forming galaxies is of great interest because it can provide a form of self-regulation. The seminal paper of Birnboim & Dekel 2003 (hereinafter BD03) investigates the stability of hot accretion shocks around disc galaxies, showing that such shocks can exist only for haloes more massive than $\approx 10^{11.5}\mathrm{M_\odot}$. In an ideal spherical flow, this hot shock would prevent cold gas from reaching the disc (or at least slow it down) and thus is likely to affect star formation. Dekel & Birnboim 2006 (hereinafter DB06) extended this approach to the study of the stability of cold streams ("filaments") within the shock–heated halo gas. They showed that the observed transition mass from blue to red galaxies at $z \simeq 0$ could be matched to the critical mass at which a stable accretion shock can exist and that stable filaments would disappear around z=1.5. These findings were also driven and further confirmed by numerical simulations

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of high redshift galaxy formation based on smoothed particle hydrodynamics (SPH), as in Kereš et al. 2005. DB06 actually presented the rise of stable hot shocks not as the origin of the quenching but only as a necessary condition for an efficient AGN feedback.

The stability of accretion shocks and filaments is driven by the competition between compressive heating and radiative cooling. The latter is itself set by the metallicity of the gas, which is thus a crucial parameter. However self-consistent modelling of the chemical enrichment in cosmological simulation is a notoriously difficult problem. In this paper, we propose to use the HORIZON-MareNostrum galaxy formation simulation, which includes a treatment of chemical enrichment, to analyse the accretion of diffuse gas on forming galaxies and revisit the accretion shocks and filamentary accretion scenarios proposed in earlier studies.

The outline of this paper is as follows: first we describe in Sec. 2 our methodology, in terms of numerical techniques and statistical measurements. We then present in Sec. 3 our main results concerning the physical properties of the accreted gas. Our findings are then discussed in the framework of earlier theoretical modelling in Sec. 4.

2 Methodology

2.1 *The MareNostrum simulation*

We have used the adaptive mesh refinement code RAMSES (Teyssier 2002) implementing metal-dependent cooling and UV heating using the Hardt and Madau background model. We have incorporated a simple model of supernovae feedback and metal enrichment using the implementation decribed in Dubois & Teyssier 2008. For high–density regions, we have considered a polytropic equation of state with a 5/3 index to model the complex, multi-phase and turbulent structure of the ISM in a simplified form (see Dubois & Teyssier 2008): the ISM is defined as gas with a density greater than $n_0 \simeq 0.1$ H/cm^3. Star formation has also been included, for ISM gas only ($n_{\rm H} > n_0$), by spawning star particles at a rate consistent with the Kennicutt law derived from local observations of star forming galaxies. The simulation was started with a base grid of 1024^3 cells and the same number of dark matter particles. The simulation was ran for a ΛCDM universe with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_B = 0.045$, $H_0 = 70$ km/s/Mpc, $\sigma_8 = 0.9$ in a periodic box of 50 h^{-1}Mpc. Our dark matter particle mass is $m_{\rm part.} \simeq 8 \times 10^6\ M_\odot$, and our spatial resolution 1 kpc *physical*. The simulation was run for 4 weeks dispatched over a full year, reaching a final redshift $z = 1.5$, where the total number of star particles at the was more than 2×10^5, and the total number of AMR cells was larger than 5×10^9.

2.2 *Mass-accretion-weighted histograms*

We have built from our simulation data a Friend–Of–Friend (FOF) halo catalogue. We put each analysed halo at rest by subtracting the mass-weighted gas velocity in a 0.5R$_{\rm vir}$ sphere. We use temperature and density probability distribution functions, and we weight the contribution to each temperature and density bin by the local accretion rate. In this way, static regions will be discarded from the analysis, while large radial velocity regions will dominate the signal, emphasizing the properties of the material being accreted. In order to explore the radial dependence of the properties of the accreted gas, we perform our measurements on a number of concentric shells spanning $[0.2-1]$R$_{\rm vir}$. In our model, the star–forming dense ISM is defined as $n_{\rm H} \geq 0.1$H/cm^3. In order to focus on smooth gas accretion rather than merging, we remove from our spherical analysis all pixels whose density exceeds this theshold.

3 Properties of diffuse gas accretion

We computed the accretion-weighted PDFs for several hundred haloes spanning dark matter masses between 10^{10}M$_\odot$ and 10^{13}M$_\odot$ between $2 \leq z \leq 5$. We then co-added (stacked) these distributions for haloes of the same mass range in order to produce an “average” PDF for a given mass scale, which we use to discuss the physical properties of the accretion flow.

3.1 *Bimodality in the temperature distribution*

Fig. 1 shows several radially–averaged accretion–weighted stacked histograms for haloes from 10^{10} to 10^{13}M$_\odot$ taken from the $z = 4$ snapshot of the simulation. We see that the accretion pattern involves two main distinct

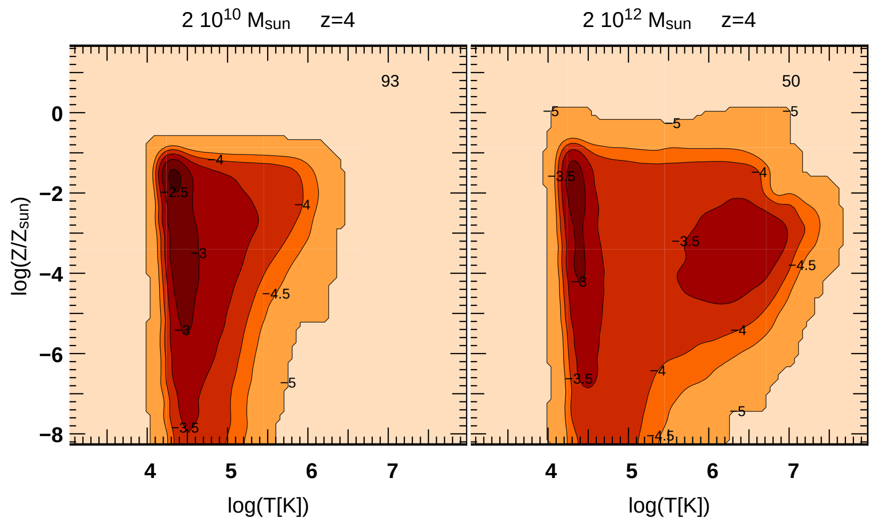

Fig. 1. Radially averaged Accretion–weighted PDFs for 2 mass bins centered on 2×10^{10} (*left*) to $2 \times 10^{12} M_\odot$ (*right*). The numbered labels on the contours give the logarithm of the PDF. When the hot phase is well developed, there is a clear bimodality in temperature.

components:

1. A cold component spanning a large range in metallicity, associated with filaments (metal-poor) as well as the close vicinity of galaxy satellites (metal-rich).

2. A hot, metal-poor component, the temperature and contribution of which increases sharply with halo mass.

3.2 Two critical masses and 3 regimes of diffuse gas accretion

Marginalizing the accretion rate over metallicity and integrating over temperature on the hot and cold temperature domains yields the hot and cold accretion rate respectively. Dividing by the total accretion rate at the chosen radius gives the contributions of the hot and cold mode to the total accretion rate.

The top left panel of Fig. 2 displays the fractions computed from the accretion-weighted histograms averaged over the entire halo (between $0.2\mathrm{R_{vir}}$ and $\mathrm{R_{vir}}$). The bottom left panel of Fig. 2 shows these fractions measured at radius $0.2R_{\mathrm{vir}}$ (galaxy vicinity) as a function of mass for various redshifts. A common feature of these plots is the increasing importance of the hot accretion mode with increasing mass, and the corresponding decreasing contribution of the cold mode, as could be foreseen from Fig. 1. The mass at which hot and cold contributions are equal defines a critical mass marking the transition between two accretion regimes.

This critical mass increases sharply with redshift, if the entire halo is considered. This evolution is the signature of a gradual disappearance of cold radially extended features, like filaments, in the massive haloes between $z = 5.4$ and $z = 2$. Therefore we note $\mathrm{M_{stream}}$ this transition mass. On the contrary, the corresponding critical mass defined using the $0.2\mathrm{R_{vir}}$ measurements shows only a slow variation with redshift, if any. It indicates that there is a stable hot shock in the inner parts of the halo as soon as $\mathrm{M_{DM}} \geq 10^{11.5-12}\mathrm{M_\odot}$, while the outer part of the halo can still be dominated by cold accretion. We note $\mathrm{M_{shock}}$ the transition mass where hot and cold fractions of the accreted gas are equal at $0.2\mathrm{R_{vir}}$. The right panel of Fig. 2 summarizes the evolution of these transition masses. The latter define 3 different regimes for diffuse gas accretion: a low mass cold accretion mode for $M < \mathrm{M_{shock}}$, a purely hot mode for $M > \max(\mathrm{M_{shock}}, \mathrm{M_{stream}})$, and a mode featuring cold streams flowing through hot shocked gas for $\mathrm{M_{shock}} < M < \mathrm{M_{stream}}$. The latter mode exists in our simulation only for $z > 2.5$. These regimes and transitions agree with those found by DB06 provided that one tunes their metallicity assumption for the filaments to almost zero, as measured in the simulation.

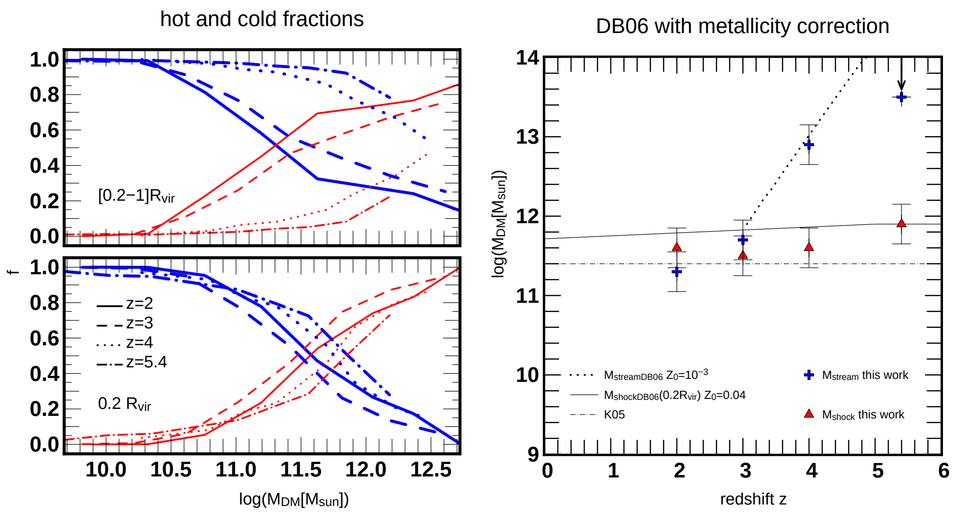

Fig. 2. *Left:* Evolution of the hot (thin line) and cold (thick lines) accreted gas mass fractions versus M_{DM} with redshift. Top: (integrated inwards down to $0.2R_{vir}$). Bottom: f_{cold} and f_{hot} on the $0.2R_{vir}$ sphere. Right: evolution of M_{shock} and M_{stream} with redshift, from our measurements and comparison to analytical modelling. The solid line shows DB06 prediction for $M_{shock}(0.2R_{vir})$ with a metallicity assumption $Z_0 = 0.02$, while the dotted line shows their prediction for M_{stream} with a metallicity assumption $Z_0 = 0.0003$. The dash dotted line shows the constant transition mass reported by Kereš et al. 2005.

4 Conclusions

We used the MareNostrum galaxy formation simulation to study the processes involved in gas accretion on galaxies. In agreement with DB06, we find that accretion proceeds in 3 different regimes: a cold accretion mode, prevailing at $M < M_{shock}$, a mode with a stable hot shock at low redshift and $M > M_{shock}$, and at high redshift, a regime where hot shocks and cold streams cohabit. However, at variance with DB06, the low metallicity of these cold streams results in their earlier disappearance, thereby showing the importance of taking chemical enrichment into account in cosmological simulations of galaxy formation.

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