The baryon fraction of ΛCDM haloes

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ABSTRACT

We investigate the baryon fraction in dark matter haloes formed in non-radiative gas-dynamical simulations of the Λ cold dark matter (CDM) cosmogony. By combining a realization of the Millennium Simulation with a simulation of a smaller volume focusing on dwarf haloes, our study spans five decades in halo mass, from 10^{10} to 10^{15} h^{-1} M_{⊙}. We find that the baryon fraction within the halo virial radius is typically 90 per cent of the cosmic mean, with a rms scatter of 6 per cent, independently of redshift and of halo mass down to the smallest resolved haloes. Our results show that, contrary to the proposal of Mo et al., pre-virialization gravitational heating is unable to prevent the collapse of gas within galactic and protogalactic haloes, and confirm the need for non-gravitational feedback in order to reduce the efficiency of gas cooling and star formation in dwarf galaxy haloes. Simulations including a simple photoheating model (where a gas temperature floor of T_{floor} = 2 \times 10^4 K is imposed from z = 11) confirm earlier suggestions that photoheating can only prevent the collapse of baryons in systems with virial temperatures T_{200} \lesssim 2.2 T_{floor} \approx 4.4 \times 10^4 K (corresponding to a virial mass of M_{200} \sim 10^{10} h^{-1} M_{⊙} and a circular velocity of V_{200} \sim 35 \text{ km s}^{-1}). Photoheating may thus help regulate the formation of dwarf spheroidals and other galaxies at the extreme faint end of the luminosity function, but it cannot, on its own, reconcile the abundance of sub-L_{⋆} galaxies with the vast number of dwarf haloes expected in the ΛCDM cosmogony. The lack of evolution or mass dependence seen in the baryon fraction augurs well for X-ray cluster studies that assume a universal and non-evolving baryon fraction to place constraints on cosmological parameters.

Key words: methods: N-body simulations – galaxies: haloes – dark matter.

1 INTRODUCTION

In the current paradigm of cosmic evolution, the Λ cold dark matter (CDM) model, structures grow from an initially smooth density field into a rich network of filaments and haloes. Initially, baryons approximately follow the collisionless dark matter, but the two components evolve differently in non-linear regions after recombination. In protogalactic haloes, for example, the kinetic energy of the collapse is thermalized in shocks by the baryons, but rapid radiative cooling losses allow for further collapse, leading to the formation of dense gaseous discs susceptible to swift transformation into stars (White & Rees 1978).

The efficient gas cooling that accompanies the collapse of protogalactic haloes at high redshift underlies one of the central apparent conflicts between hierarchical models of structure formation and observation. Indeed, Cole (1991) and White & Frenk (1991) highlighted that, in the absence of additional physics, hierarchical models predict that essentially the entire baryonic content of the Universe should have cooled at high redshift and, presumably, turned into stars by the present epoch. This is in strong contradiction with observations, which suggest that stars make up less than 5 per cent of the baryons in the Universe (for a review, see Balogh et al. 2001). To avoid this ‘cooling catastrophe’, models of galaxy formation frequently invoke various astrophysical mechanisms that counteract cooling and, in some cases, reheat cold gas.

One consequence of the cooling catastrophe is the difficulty in reconciling the galaxy luminosity function with the ΛCDM halo mass function. This was recognized in the pioneering work of White & Rees (1978), and it is now widely accepted that a heating mechanism (usually referred to as ‘feedback’) is required to explain the reduced star formation efficiency required to match the shallow faint end, as well as the sharp cut-off at the bright end, of the galaxy luminosity function (e.g. Kauffmann et al. 1999; Somerville & Primack 1999;
of halo masses, from $10^{10}$ to roughly $10^{15}$, the viability of the pre-virialization heating hypothesis in the suite of cosmological gas-dynamical simulations aimed at assessing SNe. Feedback from non-gravitational sources, such as photoionization or inhibit the accretion of gas into low-mass haloes. If efficient enough, the idea that this ‘pre-virialization’ gravitational heating might generate enough entropy, at a low redshift ($z \lesssim 2$), to substantially inhibit the accretion of gas into low-mass haloes. If efficient enough, this mechanism may offer a simple and attractive resolution to the cooling crisis, and a possible explanation of the form of the faint end of the galaxy luminosity function without the need to invoke feedback from non-gravitational sources, such as photoionization or SNe.

This is clearly an intriguing proposition, and we present here a suite of cosmological gas-dynamical simulations aimed at assessing the viability of the pre-virialization heating hypothesis in the ΛCDM cosmogony. Our simulations allow us to probe a vast range of halo masses, from $10^{10}$ to roughly $10^{15}$ h$^{-1}$ M$_\odot$. The simulations assume that baryons evolve as a non-radiative fluid; this is a conservative assumption when testing the pre-virialization hypothesis, as radiative losses would only serve to facilitate the collapse of baryons into protogalactic haloes.

We also use the same suite of simulations to explore the baryon fraction at the opposite end of the halo mass function, i.e. in galaxy cluster haloes. Adopting a non-radiative gas approach is a reasonable simplification here, since the majority of the intracluster medium (ICM) has a cooling time that exceeds the age of the Universe. The most massive galaxy clusters are of particular cosmological interest since their baryon fractions are expected to accurately trace the cosmic mean. Indeed, the comparison of cluster baryon fractions ($f_b$) with the baryon density parameter ($\Omega_b$) implied by big bang nucleosynthesis calculations provides decisive evidence for a Universe with (dark) matter density well below the critical density for closure (White et al. 1993).

In addition, the apparent redshift dependence of cluster baryon fractions can be used to constrain the geometry of the Universe (Sasaki 1996), its deceleration (Pen 1997) and by extension, the dark energy equation of state (Allen et al. 2004). These tests exploit the redshift dependence of angular diameter distances and rely on cluster baryon fractions being roughly universal and non-evolving over the redshift range where they can be observed (typically $z < 1$).

Our simulation suite provides the largest sample of haloes with non-radiative gas dynamics reported to date. This allows us to investigate the mass dependence, evolution and dispersion of halo baryon fractions with unprecedented statistical reliability. These results can be used to critically test the viability of the pre-virialization heating hypothesis and to examine the stability and evolution of cluster baryon fractions.

In the following section, we describe our simulation suite, as well as the methods and main results. We discuss them in Section 4 and conclude with a brief summary in Section 5.

### 2 SIMULATION DETAILS

To maximize the dynamic range of our halo sample, we analyse two simulations of different volumes. One (labelled ‘Low Mass’) is a high-resolution ‘zoomed-in’ simulation of a relatively small volume designed to study low-mass haloes. The other (‘High Mass’) is a gas-dynamical realization of the Millennium Simulation (Springel et al. 2005), a large volume containing many well-resolved galaxy clusters. We address numerical convergence issues by simulating the collapse of a ‘Pancake’ at varying numerical resolution. Finally, we explicitly test the robustness of our results in the Low Mass simulation by re-simulating at much higher resolution a single (‘Dwarf’) halo with virial mass $10^{10}$ h$^{-1}$ M$_\odot$. The numerical parameters and other details of the simulations are listed in Table 1.

We evolve our initial conditions in all cases using the publicly available parallel code GADGET-2 (Springel 2005), which

<table>
<thead>
<tr>
<th>Simulation</th>
<th>$m_{gas}$ ($h^{-1}$ M$_\odot$)</th>
<th>$m_{dm}$ ($h^{-1}$ M$_\odot$)</th>
<th>$N_p$</th>
<th>$\epsilon_{com}$ (kpc)</th>
<th>$\Omega_b$</th>
<th>$\Omega_\Lambda$</th>
<th>$L$ ($h^{-1}$ Mpc)</th>
<th>$z_{init}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Mass</td>
<td>$3.12 \times 10^9$</td>
<td>$1.42 \times 10^9$</td>
<td>$5.0 \times 10^9$</td>
<td>100.0$^*$</td>
<td>0.045</td>
<td>0.25</td>
<td>500</td>
<td>49</td>
</tr>
<tr>
<td>Low Mass</td>
<td>$1.65 \times 10^9$</td>
<td>$8.70 \times 10^8$</td>
<td>$2.6 \times 10^9$</td>
<td>5.0</td>
<td>0.040</td>
<td>0.25</td>
<td>100</td>
<td>127</td>
</tr>
<tr>
<td>Dwarf</td>
<td>$1.20 \times 10^9$</td>
<td>$7.80 \times 10^8$</td>
<td>$3.4 \times 10^9$</td>
<td>0.4</td>
<td>0.040</td>
<td>0.30</td>
<td>35.325</td>
<td>74</td>
</tr>
<tr>
<td>Pancake</td>
<td>$1.20 \times 10^9$</td>
<td>$7.83 \times 10^8$</td>
<td>$3.5 \times 10^9$</td>
<td>10.0</td>
<td>0.040</td>
<td>0.30</td>
<td>N/A</td>
<td>145</td>
</tr>
</tbody>
</table>
non-radiative\(^1\) baryon physics implemented by an entropy-conserving formulation of smoothed particle hydrodynamics (SPH) (Springel & Hernquist 2002). We smooth SPH quantities over 40 neighbour particles in each simulation, with the exception of High Mass, in which 33 neighbours were used.

2.1 High Mass simulation

Our sample of high-mass haloes is drawn from a non-radiative gas-dynamical realization of the Millennium Simulation. It adopts the same displacement field and cosmology as the original simulation, but has lower mass resolution: \(5 \times 10^8\) gas and dark matter particles within a periodic simulation box of side 500 \(h^{-1}\) Mpc. The baryon density parameter \(\Omega_b = 0.045\) results in particle masses of \(m_{\text{pm}} = 3.12 \times 10^9 h^{-1} \text{M}_\odot\); for the dark matter we adopt \(\Omega_{\text{dm}} = 0.25\), implying a particle mass of \(m_{\text{pm}} = 1.42 \times 10^{10} h^{-1} \text{M}_\odot\). We choose a comoving gravitational softening of \(100 h^{-1}\) kpc until \(z = 3\), at which point it is fixed in physical units to \(25 h^{-1}\) kpc. Gravitational forces are computed in this simulation with a TreePM algorithm, whereby short-range forces are computed by hierarchical multipole expansion and long-range forces are computed with a particle-mesh (PM) scheme based on Fast Fourier Transforms (FFTs). A mesh of 1024\(^3\) cells was adopted for the PM algorithm. Further discussion of the simulation details and analysis will be presented in a forthcoming paper (Pearce et al., in preparation).

2.2 Low Mass simulation

In order to analyse a representative region of the Universe whilst still resolving low-mass haloes, we simulate the evolution of a spherical region of radius \(7 h^{-1}\) Mpc, identified at \(z = 0\) in a simulation of a box \(100 h^{-1}\) Mpc on a side with the same cosmological parameters as the Millennium Simulation. The sphere was chosen at random from a sample of spherical regions with mean density within 10 per cent of the cosmic mean, and devoid of haloes with mass \(M_{200} > 10^{13} h^{-1}\) \(\text{M}_\odot\), in order to prevent the region from being dominated by a single halo. Randomly placed spheres satisfy the density selection criterion slightly less than 10 per cent of the time, since the volume is dominated by underdense regions. Approximately one-third of spheres satisfying the density criterion lack haloes more massive than \(10^{13} h^{-1} \text{M}_\odot\).

Our initial conditions are generated by resampling the region with a greater number of particles and adding additional short wavelength perturbations, whilst coarse sampling the external mass distribution with multimass collisionless particles to reproduce the large-scale gravitational field. Our resampling algorithm is based upon the procedure outlined by Frenk et al. (1996), and is described in detail by Power et al. (2003). Gas is added to the high-resolution region by splitting each particle into a dark matter particle and a gas particle, with mass ratio given by the adopted baryon and dark matter density parameters. This implies that each gas particle has a corresponding dark matter ‘partner’ associated with a unique volume element at high redshift, a useful feature when tracing the differences in the evolution of the two components in the non-linear regime.

The Low Mass simulation features \(2.5 \times 10^6\) gas particles of masses \(m_{\text{pm}} = 1.65 \times 10^8 h^{-1} \text{M}_\odot\) and an equal number of high-resolution dark matter particles, of mass \(m_{\text{dm}} = 8.70 \times 10^8 h^{-1} \text{M}_\odot\). At this resolution, the simulated volume yields a sample of \(~1300\) well-resolved (i.e. \(N_{\text{pm}} > 150\)) low-mass haloes at \(z = 0\) whilst remaining relatively computationally inexpensive. We adopt a TreePM algorithm to compute gravitational forces, this time also using a second PM grid, nested within the primary grid and enclosing the high-resolution particles, to compute intermediate-range forces. We use PM meshes of 256\(^3\) cells in this case.

2.3 Dwarf simulation

In order to assess the robustness of our results for low-mass haloes, we re-simulate a single dwarf halo \((10^{10} h^{-1} \text{M}_\odot)\) at much higher resolution than its counterparts in Low Mass. Because pre-virialization heating is expected to be most effective in haloes assembling late, we select for resimulation a dwarf halo with relatively late formation time for its mass. The most massive progenitor first exceeds half the final mass of the halo at \(z = 0.6\), whilst the extensions to the Press–Schechter theory (Press & Schechter 1974) described by Lacey & Cole (1993) suggest that the most probable formation time for a halo of this mass is \(z \sim 2\).

We selected the halo from a parent simulation of box length 35.325 \(h^{-1}\) Mpc and density parameters \((\Omega_m, \Omega_{\Lambda} = 0.3, 0.7)\). We apply the same resimulation technique as for Low Mass, using \(3.4 \times 10^4\) gas and high-resolution dark matter particles. We adopt a baryon density parameter of \(\Omega_b = 0.04\), which implies particle masses of \(m_{\text{pm}} = 1.20 \times 10^9 h^{-1} \text{M}_\odot\) and \(m_{\text{dm}} = 7.8 \times 10^8 h^{-1} \text{M}_\odot\). At \(z = 0\), the halo has mass \(M_{200} = 9.5 \times 10^8 h^{-1} \text{M}_\odot\), virial radius \(r_{200} = 34.5 h^{-1}\) kpc and circular velocity \(v_{200} = 35 \text{ km s}^{-1}\). As for the Low Mass simulation, we adopt the TreePM gravity algorithm with two PM meshes. In this case, meshes of 128\(^3\) cells were employed.

2.4 Pancake simulation

The pre-virialization mechanism outlined by M05 assumes that gas is heated during the pancake-like collapse of the large-scale structure within which dwarf haloes are embedded. It is therefore important to explore whether our numerical techniques are suitable to describe this process accurately, as well as whether the results are not artificially marred by limited numerical resolution.

We investigate this by simulating the collapse of an idealized pancake with similar numerical resolution as that of the Low Mass simulation, and then vary the resolution in order to assess convergence. The simulation involves the collapse of a uniform spherical region of mass \(3 \times 10^{12} h^{-1} \text{M}_\odot\), initially perturbed so that it collapses along one axis to form a flattened pancake at \(z = 2\). We use a ‘glass’ rather than a grid in order to minimize the artefacts introduced by anisotropies in the grid. The desired dynamics are achieved by compressing the sphere along one axis and expanding it by half of the compression factor along the other two axes, with initial velocities computed using linear theory. We compute gravitational forces in this simulation using only a tree algorithm.

The choice of parameters for this simulation is motivated by the discussion of M05, who argue that such ‘pancakes’ might represent the typical environment where dwarf galaxy haloes are formed, and that pre-virialization heating might have been missed in early simulations because of inadequate resolution. As noted by M05, a collapsing pancake forms shocks on both sides, so a faithful treatment of its thermodynamic evolution requires \(\geq 8\) smoothing lengths across its collapsing axis. Following M05, and assuming that shocks operate as the collapsed structure approaches an overdensity of \(\sim 10\), this implies a pancake thickness of \(200 h^{-1}\) kpc (comoving) and a

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\(^1\) We avoid the common practice of terming non-radiative simulations ‘adiabatic’, since they include non-adiabatic shocks.
minimum resolution of $25\,h^{-1}\text{kpc}$, again comoving. We fulfill this criterion using a particle mass similar to that of the Low Mass simulation. At an overdensity of $10\Omega_b\rho_c(z)$, a mass of $40\,m_p$ particles (comparable to what is used to define the SPH smoothing length scale) is contained within a sphere of comoving smoothing length $h_{\text{sm}} \sim 25\,h^{-1}\text{kpc}$.

3 ANALYSIS AND RESULTS

Fig. 1 shows various snapshots of the Low Mass simulation. Each box is $10\,h^{-1}\text{Mpc}$ on a side and shows the positions of gas particles, colour coded according to density. This figure clearly shows the highly anisotropic nature of the large-scale structure, but also highlights the points that many dwarf dark matter haloes had already collapsed by $z \sim 2$. As we discuss below, this has important implications for the efficiency of pre-virialization heating and its effects on the baryon fraction of collapsed systems.

3.1 Halo finding algorithm

We use a friends-of-friends group finding algorithm (Davis et al. 1985) with a short linking length ($b = 0.05$) to locate the cores of haloes in the simulation volumes. The centres of these haloes are used as starting points for an iterative algorithm that finds spherically overdense regions of mean enclosed density $200\rho_c(z)$, whose centres coincide with their centres of mass. We define the virial radius, $r_{200}$, as the radius of this sphere. Other ‘virial’ quantities quoted for haloes refer to measurements within this radius, unless otherwise specified.

We consider only haloes with at least 150 dark matter particles in order to minimize the effects of poor numerical resolution, and clean the sample by removing haloes partially contained within other haloes. In the case of Low Mass, we also disregard haloes located closer than $200\,h^{-1}\text{kpc}$ from the boundary of the resimulated region at $z = 0$, since they may have been subject to boundary effects. This criterion further guarantees that all haloes considered from this

Figure 1. Redshift progression of the projected gas density within a cube of side $10\,h^{-1}\text{Mpc}$ (comoving) in the Low Mass simulation. The progression clearly illustrates that by $z = 2$ many dark matter haloes have already collapsed, driving their associated gas to high overdensities. Such gas is afforded stability against the shocks that develop as the large-scale environment, within which it is embedded, collapses into pancakes and filaments.
The baryon fraction of ΛCDM haloes are free from contamination by low-resolution boundary particles.

3.2 Baryon fractions

3.2.1 High Mass

The right-hand panels of Fig. 2 show the baryon fraction in haloes identified in the High Mass simulation at $z = 1$ and 0. These panels show the largest sample of haloes simulated with non-radiative gas physics reported to date, with approximately 49,500 and 115,000 haloes resolved at $z = 1$ and 0, respectively. The panels show that the baryon fraction is independent of mass, and has not evolved at least since $z = 1$, the highest redshift for which cluster baryon fractions can be estimated reliably from X-ray observations (e.g. the observations of Allen et al. 2004 span the redshift range $0.07 < z < 0.9$).

The mean cluster baryon fraction within the virial radius is approximately 90 per cent of the cosmic mean, with relatively small scatter; the rms dispersion is less than 3 per cent for haloes of mass $M_{200} \gtrsim 3 \times 10^{14} h^{-1} M_\odot$, and the difference between the 10th and 90th percentiles is always less than 7.5 per cent over the same mass range. The scatter remains small for all well-resolved haloes; the rms scatter is less than 6 per cent for haloes resolved by at least 500 dark matter particles. This result is in broad agreement with previous simulations of cluster baryon fractions in the non-radiative regime using SPH codes (e.g. Navarro, Frenk & White 1995; Eke, Navarro & Frenk 1998; Frenk et al. 1999; Ettori et al. 2006).

These results are only weakly dependent on radius; within a radius encompassing a mean inner density 500 times greater than critical, $r_{500}$, the results are very similar to those within $r_{200}$: for $M_{200} \gtrsim 3 \times 10^{14} h^{-1} M_\odot$ the baryon fraction remains, on average, 90 per cent with a rms dispersion of 3 per cent. This radius, which is $\sim 0.7 r_{200}$ for a NFW profile (Navarro, Frenk & White 1996, 1997) with concentration $c = 5$, is roughly the maximum radius for which total cluster masses can be estimated reliably from X-ray observations (e.g. Vikhlinin et al. 2006).

3.2.2 Low Mass

The left-hand panels of Fig. 2 show that a similar result applies to the halo sample identified in the Low Mass simulation. The baryon fraction of galactic and dwarf haloes is also about 90 per cent of the cosmic mean, and shows no discernible dependence on mass or redshift.

A notable downturn is observed below about $10^{10} h^{-1} M_\odot$, but this may be ascribed to the poorer resolution affecting such haloes, since an underestimate of the gas density at accretion shocks leads to artificially high post-shock entropies. Note that a similar downturn is also seen in the High Mass sample for haloes resolved with fewer than $\sim 500$ particles. Downward arrows show the mass scale corresponding to 500 dark matter particles in each simulation.

3.2.3 Dwarf

Fig. 2 suggests that for haloes resolved with more than $\sim 500–1000$ particles, numerical resolution does not affect the measured baryon fractions. Further supporting evidence comes from the results obtained for the high-resolution individual Dwarf halo. These are shown in Fig. 2 with a filled triangle, and are consistent with Low Mass haloes of similar mass.

![Figure 2](https://academic.oup.com/mnras/article-abstract/377/1/41/1077791) - Baryon fractions, in units of the universal value, of well-resolved haloes ($N_{dm} > 150$) drawn from the Low Mass (left-hand panels) and High Mass (right-hand panels) simulations at $z = 1$ (upper panels) and $z = 0$ (lower panels). The large dots and error bars show the mean and rms of the distribution, respectively. The green triangle marks the baryon fraction of the halo in the Dwarf simulation. The upper horizontal axis gives the equivalent number of dark matter particles at a given mass scale. The downward arrows in each plot illustrate the mass scale corresponding to 500 dark matter particles.
radial extension of 1.5

as was increased by a factor of 8. Gravitational softenings were scaled by running a higher resolution case where the number of particles test the effect of resolution by re-running the Pancake simulation. The median specific entropy reaches typically underestimation of the true densities: entropies are therefore typically underestimate of the entropy jump in numerical simulations of pancake-like collapse. Actually, poor resolution leads typically to the transition becomes notably sharper as the resolution increases. This test shows that limited resolution does not lead to a substantial underestimate of the entropy jump in numerical simulations of pancake-like collapse. Actually, poor resolution leads typically to underestimation of the true densities: entropies are therefore typically overestimated in poor resolution simulations. This result, together with the consistency between the Low Mass and Dwarf simulations, gives us confidence that baryon fractions in our simulations are not unduly affected by resolution effects.

3.2.4 Pancake

One may still worry that, despite the apparent convergence of the results shown in Fig. 2, the numerical resolution is insufficient to capture the shocks during the pancake collapse phase that accompanies the formation of haloes. We can test this by examining the Pancake simulation.

Fig. 3 shows the evolution of the entropy (measured by $s = \frac{T}{n_e^2}$), and of the temperature of the gas during the collapse of the sphere to a pancake configuration. Note that when computing the electron density, $n_e$, we assume the gas is fully ionized and of primordial composition. At $z = 2$, the system reaches maximum asphericity, and is well described by a plane of comoving thickness 25 $h^{-1}$ kpc (cf. comoving softening of 10 $h^{-1}$ kpc) and comoving radial extension of 1.5 $h^{-1}$ Mpc.

The collapse heats gas to a median temperature of $3 \times 10^4$ K, and the median specific entropy reaches $s \simeq 1$ keV cm$^2$. We explicitly test the effect of resolution by re-running the Pancake simulation with particle numbers reduced by factors of 8 and 64 relative to the standard resolution of Low Mass; we complete the resolution study by running a higher resolution case where the number of particles was increased by a factor of 8. Gravitational softenings were scaled as $\epsilon \propto N_p^{-1/3}$.

As shown in Fig. 3, the post-shock median entropy and temperature jumps are quite insensitive to numerical resolution, although the transition becomes notably sharper as the resolution increases. This test shows that limited resolution does not lead to a substantial underestimate of the entropy jump in numerical simulations of pancake-like collapse. Actually, poor resolution leads typically to underestimation of the true densities: entropies are therefore typically overestimated in poor resolution simulations. This result, together with the consistency between the Low Mass and Dwarf simulations, gives us confidence that baryon fractions in our simulations are not unduly affected by resolution effects.

3.3 Photoheating

The one feedback mechanism that is certainly present at early times is associated with the energetic photons that reionized the Universe at high redshift. This has long been recognized as having the potential to inhibit the formation of galaxies in low-mass haloes, although there is still no consensus concerning the mass scale below which photoheating becomes effective at halting galaxy formation (Blumenthal et al. 1984; Efstathiou 1992; Quinn, Katz & Efstathiou 1996; Thoul & Weinberg 1996; Bullock, Kravtsov & Weinberg 2000; Benson et al. 2002). Most semi-analytic galaxy formation models have so far adopted the prescription of Gnedin (2000) to determine the gas accreted by haloes for given IGM pressure, but recent results presented by Hoeft et al. (2006) suggest that Gnedin’s approach may substantially overestimate the mass scale of photoheating.

This motivates us to include a simple photoionization heating model in our simulations. The aim is twofold. On the one hand, we wish to shed light on the disagreement about the effects of photoheating on gas fractions, but, on the other hand, we would also like to explore whether photoheating may act to suppress the efficiency of gas accretion in the early phases of the hierarchy, facilitating and enhancing the thermodynamic effect of pancake-driven shocks.

We investigate the combined effect of gravitational and photoheating by re-running the Dwarf and Low Mass simulations, again with non-radiative gas physics, but, motivated by the 3-yr Wilkinson Microwave Anisotropy Probe (WMAP) data (Spergel et al. 2006), imposing a spatially uniform temperature floor for all gas particles at $z = 11$. To aid as much as possible the pre-virialization generation of entropy, we adopt for the temperature floor a rather high value, $T_{\text{floor}} = 2 \times 10^4$ K, consistent with the maximum temperature of the IGM at mean density, as probed by quasi-stellar object (QSO) absorption spectra (Schaye et al. 2000).

This should clearly impact gas accretion on dwarf galaxy haloes and, in particular, our Dwarf halo, where the virial temperature is only $\approx 4.4 \times 10^4$ K at $z = 0$, only a factor of 2.2 above $T_{\text{floor}}$. We therefore expect that a considerable fraction of the gas bound to small halo progenitors at high redshift should be photoevaporated from this structure.

Fig. 4 illustrates the effect of the additional heating on the baryon fractions of the Low Mass halo sample (open circles) and compares...
them with the results of the non-radiative run (filled circles). Photoheating introduces a well-defined mass scale below which gas accretion is strongly suppressed. Below \( M_{200} \sim 10^{10} h^{-1} M_\odot \), haloes are able to retain less than one half of their share of baryons within their virial radii; the effect is as large as 90 per cent in haloes below \( 3 \times 10^9 h^{-1} M_\odot \), corresponding to an effective virial temperature very similar to the photoheating temperature floor.

4 DISCUSSION

The main result of the previous section is that, in the non-radiative approximation, the baryon fraction of ΛCDM haloes is independent of redshift as well as of mass, in the range resolved by our simulations (\( 10^{10} \text{–} 10^{15} h^{-1} M_\odot \)). Photoionization reduces the baryon fraction only in haloes with virial temperature comparable to that imposed by the ionizing photons, typically just above \( 10^4 \) K. We discuss below the implication of these results for models of galaxy formation and for the interpretation of observations of baryon fractions in clusters.

4.1 Baryon fraction bias

The lack of dependence of baryon fractions on halo mass is intriguing, as is the fact that the mean value within the virial radius is only \( \sim 90 \) per cent of the cosmic mean. The same result has been observed in other simulations (Navarro, Frenk & White 1995; Eke, Navarro & Frenk 1998; Frenk et al. 1999; Kravtsov, Nagai & Vikhlinin 2005; Ascasibar et al. 2006), and has been ascribed to the collisional versus collisionless nature of the baryons and dark matter, coupled to the hierarchical assembly of haloes in the ΛCDM cosmogony. Indeed, during the many mergers that mark the formation of a halo, shocks act to stop the gas whilst the dark matter streams through freely. This leads to a temporary spatial offset between dark and gaseous components during which energy and angular momentum are transferred from the dark matter to the baryons, as discussed in detail by Navarro & White (1993). The energy gained during mergers results in a more extended gaseous component, and an overall (slight) reduction in the baryon fraction relative to the cosmic mean.

4.2 Pre-virialization heating

The results of Fig. 2 imply that pre-virialization heating is ineffective at preventing the collapse of baryons into low-mass haloes, even for masses as low as \( 10^{10} h^{-1} M_\odot \). Fig. 4 compares the baryon fractions of Low Mass haloes at \( z = 0 \) (filled circles) with the predictions of the M05 model (dotted line). M05 argue that the IGM in low-mass haloes should have been heated by shocks to roughly \( 10^2 \) keV cm\(^2\) prior to halo assembly, and that this would lead to a reduction of \( \geq 50 \) per cent in the baryons filling haloes of mass \( \sim 6 \times 10^{11} h^{-1} M_\odot \). M05 propose a fitting formula to characterize this effect;

\[
\frac{f_b^{\text{halo}}}{f_b^{\text{vir}}} = \frac{1}{(1 + M_\rho/M_\rho^*)^\alpha},
\]

where \( \alpha = 1 \) and \( M_\rho = 5 \times 10^{11} h^{-1} M_\odot \) is a characteristic mass scale. This function clearly fails to reproduce our results, and suggests that the hypotheses on which M05 base their model are not satisfied in our simulations.

The main premise of M05’s model is that most low-mass haloes form in extremely aspherical regions where their assembly might be delayed, allowing for pancake-driven shocks to elevate the entropy of the IGM prior to halo assembly. Our simulations, however, indicate otherwise.

First, low-mass haloes surviving to the present were, at the time of their formation, in regions where pre-virialization shocks were weaker than envisaged by M05. For example, we find a typical post-collapse entropy of \( \sim 1 \) keV cm\(^2\) in our pancake collapse simulations, about an order of magnitude lower than adopted by M05 to compute the model shown by the dotted curve in Fig. 4. Qualitatively, our findings concur with those of Sandvik et al. (2007), whose excursion set analysis led them to conclude that the progenitor pancakes of dwarf galaxy haloes are typically one or two orders of magnitude less massive than required by the M05 model. Our baryon fractions drawn from the simulations suggest that the halo assembly process is approximately scale free; if pre-virialization heating does indeed occur, it affects all haloes in similar measure, leaving no particular signature in low-mass haloes.

Secondly, the material destined to make a low-mass halo collects into dense, early-collapsing clumps prior to the collapse of the surrounding ‘pancake’. The pancake, in other words, is not a uniformly aspherical structure where shocks may propagate freely, but rather a large-scale feature where a substantial fraction of the mass is in collapsed clumps.

We illustrate this in Fig. 5, where we plot (dotted line) the fraction of the final Dwarf halo gas that resides in collapsed structures, as quantified by the condition \( \rho > 10 \rho_{\text{crit}}(z) \). By this rather strict measure, half the Dwarf gas is already in collapsed structures prior to \( z \sim 2 \), although by then the most massive halo progenitor (solid line) has only about \( \sim 25 \) per cent of the final mass. This early aggregation of the halo gas into dense structures prevents it from being shock heated by the pancake-driven shocks, reducing further the pre-virialization heating efficiency.

4.3 Photoheating

As shown in Fig. 4, the baryon fraction may be reduced because of heating by a photoionizing background, but the effect (at \( z = 0 \)) is restricted to haloes with virial temperatures \( \lesssim 2.7 T_{\text{floor}} \). This implies that ionizing photons, which are unlikely to heat the gas to temperatures much higher than \( \sim 2 \times 10^4 \) K, are only able to influence the formation of galaxies in haloes less massive than...
\(10^{10} h^{-1} M_\odot\). Our results for the baryon fraction in this case are well described by equation (1), but with the revised parameters suggested by M05 for their photoheating model: \(\alpha = 3\) and \(M_s = 1.7 \times 10^9 h^{-1} M_\odot\); we show this fit in Fig. 4 as a solid line.

The results shown in Fig. 4 agree with those of Hoeft et al. (2006), who used a more detailed treatment of the UV background; the similarity of our findings is rather encouraging. We concur with their assessment that the characteristic mass scale of photoevaporation is probably considerably lower than derived from the filtering mass formalism of Gnedin (2000). Thus, although photoheating can reduce the baryon fraction in low-mass systems, it appears to be less efficient at shaping the extreme faint end of the galaxy luminosity function than previously inferred through semi-analytic modelling (e.g. Benson et al. 2002; Somerville 2002).

Our results seem to be robust to numerical resolution, as shown by the good agreement between the baryon fraction of the Low Mass and the Dwarf haloes plotted in Fig. 4. In the latter case, photoheating reduces the baryon fraction by 50 per cent but there is no evidence that pre-virialization has played a role; indeed, inspection of the evolution of the collapsed gas fraction (red dashed line in Fig. 5) shows no discernible feature that may be associated with the collapse of the large-scale structure.

M05’s pre-virialization model, shown as a dotted line in Fig. 4, requires baryon fractions to be halved in haloes as massive as \(5 \times 10^{13} M_\odot\); this is an order of magnitude larger than the mass of haloes significantly affected by photoheating and pre-virialization in our simulations. Our results suggest, then, that other feedback mechanisms are required to match the faint end of the galaxy luminosity function in the \(\Lambda CDM\) scenario.

4.4 Application to cluster surveys

Our High Mass simulation also features over 115,000 galaxy or galaxy-cluster sized haloes, and demonstrates that, in the non-radiative regime, cluster baryon fractions are independent of virial mass, display little dispersion and do not evolve significantly over the redshift range \(0 < z < 1\). Observationally, mass profiles of clusters are typically only estimated reliably out to a maximum radius of \(r_{500}\); the results within that radius are very similar to those plotted in Fig. 2 at the virial radius. In haloes where the region interior to \(r_{500}\) is resolved by at least 500 dark matter particles, the mean cluster baryon fraction within \(r_{500}\) at \(z = 0\) remains approximately 90 per cent of the cosmic mean, again with a rms dispersion of \(\sim \sigma = 6\) per cent.

The key to the applicability of our results to cosmological tests is the validity of our non-radiative treatment of the ICM. Whilst the failure of purely non-radiative models to match some of the global scaling relations exhibited by clusters is well documented (e.g. Evrard & Henry 1991; Kaiser 1991; Navarro et al. 1995; Eke et al. 1998), this does not necessarily imply that non-radiative models give the wrong fraction of hot baryons in observed clusters. Since the \(r^2\) dependence of thermal bremsstrahlung implies that the X-ray emissivity of clusters is dominated by the central region, it is possible to obtain agreement with the observed X-ray scaling relations by modifying only the central gas density (e.g., with radiative cooling or AGN feedback), whilst leaving the density of the bulk of the gas unchanged (e.g. Balogh, Babul & Patton 1999; McCarthy, Babul & Balogh 2002; Voit et al. 2002, 2003; McCarthy et al. 2004).

It should be noted, however, that the X-ray luminosity–temperature relation can also be explained by models that do affect baryons at large radii (e.g. Kay et al. 2004; Kravtsov et al. 2005; Ettori et al. 2006). In such models, the hot baryon fraction at \(r_{500}\) can be reduced by up to \(\sim 30\) per cent, even for clusters with \(M_{200} > 10^{13} h^{-1} M_\odot\). However, such large-scale reductions by means of cooling and star formation conflict with optical constraints (e.g. Balogh et al. 2001), and the necessary level of feedback from SNe also appears unfeasibly high (Benson et al. 2003; Scannapieco & Oh 2004).

The effect of non-gravitational processes on the large-scale properties of rich clusters remains a source of debate. We anticipate that analyses of the large samples of rich clusters provided by the Chandra and XMM–Newton observatories will foster the development of a definitive picture of the ICM. This picture may well show that baryons at large radii are only minimally affected by non-gravitational processes, thus validating our results that rich cluster baryon fractions do not evolve for \(z < 1\) and exhibit little dispersion.

5 CONCLUSIONS

We have measured the baryon fractions of a large sample of haloes drawn from a suite of non-radiative gas-dynamical simulations of the \(\Lambda CDM\) cosmology. The haloes span five orders of magnitude in virial mass, from dwarf galaxy haloes to large clusters. Within the virial radius, the baryon fraction averages 90 per cent of the cosmic mean, with a fairly small dispersion (\(\sim 6\) per cent rms) and shows no dependence on redshift for well-resolved systems. This is at odds with the ‘pre-virialization’ gravitational heating proposed by M05. Pre-virialization, if at all present, plays only a minor role in setting the budget of baryons that accrete into low-mass haloes.

Photoheating, modelled here as resulting from a uniform temperature ‘floor’ of \(2 \times 10^4 K\) imposed on the baryons from \(z = 11\), is only able to reduce the baryon fraction in haloes with virial temperatures comparable to the photoheating floor. The absence of a strong mass trend in the baryon fractions of low-mass haloes highlights the need for non-gravitational feedback as a means to regulate gas cooling and star formation in low-mass haloes, in order to reconcile the \(\Lambda CDM\) halo mass function with the observed galaxy luminosity function.

At \(r_{500}\), the typical maximum radius at which current X-ray telescopes can probe cluster temperatures, the baryon fraction remains similar to that at \(r_{200}\), again with similarly small dispersion. It seems unlikely that non-gravitational physics can substantially modify the baryon fraction of massive \((M_{200} \gtrsim 3 \times 10^{14} M_\odot)\) clusters within \(r_{500}\); we therefore conclude that studies of the baryon fraction of clusters, as a function of redshift, offer a good prospect for a robust and reliable estimate of the matter density parameter and the dark energy equation of state.

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