Balancing the baryon budget: the fraction of the IGM due to galaxy mergers

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ABSTRACT

Observations indicate that roughly 60 per cent of the baryons may exist in a warm-hot intergalactic medium (WHIM) at low redshifts. Following up on previous results showing that gas is released through galaxy mergers, we use a semi-analytic technique to estimate the fraction of gas mass lost from haloes solely due to mergers. We find that up to ~25 per cent of the gas in a halo can unbind over the course of galaxy assembly. This process does not act preferentially on smaller mass haloes; bigger haloes always release larger amounts of gas in a given volume of the Universe. However, if we include multiphase gas accretion on to haloes, we find that only a few per cent is unbound. We conclude that either non-gravitational processes may be in play to heat up the gas in the galaxies prior to unbinding by mergers or most of the baryons in the WHIM have never fallen into virialized dark matter haloes. We present a budget for stocking the WHIM compiled from recent work.

Key words: methods: numerical – galaxies: evolution – galaxies: haloes – galaxies: interactions – intergalactic medium – cosmology: large-scale structure of Universe.

1 INTRODUCTION

The baryon budget shows significant evolution from $z \sim 3$, and results in an apparent baryon deficit today (Fukugita, Hogan & Peebles 1998; Fukugita & Peebles 2004). At high redshift, most of the baryonic mass is in the Ly$\alpha$ forest (Fukugita et al. 1998; Fukugita & Peebles 2004), while at low redshifts over half of the baryons are as yet undetected. The consensus is that the majority of the ‘missing’ baryons are actually in regions of low overdensity, as yet undetected. The consensus is that the majority of the ‘missing’ baryons are actually in regions of low overdensity, $\delta_{\rho}/\rho \sim 10–100$ (e.g. Cen & Ostriker 1999, 2006; Davé et al. 1999, 2001; Kang et al. 2005; Dolag et al. 2006; Davé & Oppenheimer 2007) with temperatures in the range $10^{5}–10^{7}$ K – commonly referred to as the warm-hot intergalactic medium (WHIM).

The immediate question is: how is this WHIM produced? Some form of mass and energy injection is essential to create this hot reservoir of gas; this form of feedback must both regulate the gas in galaxies and the metal content of the intergalactic medium (IGM).

There has been much numerical work to incorporate various feedback mechanisms in an attempt to solve this puzzle (e.g. Cen & Ostriker 1999, 2006; Davé et al. 2001; Nath & Silk 2001; Kang et al. 2005; Davé & Oppenheimer 2007, and references therein). Cosmological simulations seem to suggest that gravitational collapse during galaxy formation can produce and maintain the majority of the WHIM at $10^{5}–10^{7}$ K (Cen & Ostriker 1999, 2006; Davé et al. 1999; Croft et al. 2001; Davé & Oppenheimer 2007). Supernova (SN) feedback provides another avenue to generate the WHIM; for starbursts of $100 M_\odot$ yr$^{-1}$, as much as 20 per cent of the hot gas in a Milky Way mass galaxy can be unbound (Scannapieco et al. 2006; Kobayashi, Springel & White 2007). However, SNe feedback may be a self-regulating process, in that a starburst also heats the remaining gas and may damp the star formation rate, which in turn would reduce the fraction of unbound gas (e.g. Scannapieco et al. 2008). Combining these effects, it is commonly thought that galaxies with host halo mass $\geq 10^{11} M_\odot$ lose $\lesssim 10$ per cent of their gas through SN feedback, while low-mass haloes may be entirely depleted of gas by this mechanism (Yepes et al. 1997; Mac Low & Ferrara 1999; Efstathiou 2000; Scannapieco et al. 2006). A third possibility is that the radiation from an accreting supermassive black hole could power large-scale winds to blow mass out of the galaxy (see Scannapieco & Oh 2004; Hopkins et al. 2005a,b, 2006; Murray, Quataert & Thompson 2005; Croton et al. 2006; Sijacki et al. 2007). For a fixed amount of energy, all the non-gravitational feedback mechanisms are more effective in low-mass galaxies due to their shallower potential. However, observations suggest that low-mass galaxies are in general more gas rich and are less likely to have suffered a gas blowout (Kannappan 2004; Geha et al. 2006).

In Sinha & Holley-Bockelmann (2009, hereafter SH09), we show that hot gas is driven into the IGM by galaxy mergers. The amount of hot halo gas lost depends strongly on the energy of the merger; it is possible for low-mass galaxies to retain their gas in this scenario during low-speed or distant encounters. However, SH09 only estimated the mass lost during a single merger. When all the mergers in the Universe are considered, this could heat and drive a significant portion of the total baryon budget into the WHIM. In principle,
this process could join active galactic nuclei (AGN) and star formation feedback as a way to populate the WHIM, and we find that this method operates preferentially in more massive haloes. To estimate the total fraction of gas released by mergers, we construct a series of analytic halo merger trees using a publicly available\(^1\) semi-analytic extended Press–Schechter ( EPS) code (Parkinson, Cole & Helly 2008).

In Section 2 we describe the theory of halo merger trees; in Section 3 we outline the experiments designed to track the gas ejected via galaxy mergers; in Section 4 we present the results for the halo gas ejected by this process and Section 5 contains the discussion.

## 2 CONSTRUCTING MERGER TREES

Observations reveal that we live in low-density, \(\Lambda\)-dominated flat Universe (Perlmutter et al. 1997; Riess et al. 1998; Spergel et al. 2007; Komatsu et al. 2009). In such a Universe, haloes form hierarchically, with smaller haloes forming early on and merging into larger structures at later times. This process of halo formation is dictated by gravitational processes, and an analytic formalism yields the number density of haloes as a function of mass and redshift (Press & Schechter 1974). However, this does not constrain the merger rates for any given halo as a function of redshift. To this end, the Press–Schechter formalism has been extended to calculate a merger history of a halo in the form of a binary merger tree (Bond et al. 1991; Bower 1991; Lacey & Cole 1993). These merger trees are computationally much less expensive than an \(N\)-body simulation, and are widely used to explore and constrain theories of galaxy evolution, black hole growth, etc. We use the technique here to estimate the gas lost to the WHIM via galaxy mergers.

In the EPS model of Parkinson et al. (2008), the conditional mass function \(f(M_1|M_2)\) gives the fraction of halo mass \(M_1\) at a redshift \(z_1\) that was contained in a progenitor halo of mass \(M_1\) at a previous redshift \(z_2\):

\[
f(M_1|M_2)\,d\ln M_1 = \frac{\sqrt{\pi}}{2} \frac{\sigma^2_1 (\delta_1 - \delta_2)}{\sigma^2_2 (\delta_2 - \sigma^2_2)^{1/2}} \times \exp\left[ -\frac{1}{2} \frac{(\delta_1 - \delta_2)^2}{\sigma^2_1 - \sigma^2_2} \right] \frac{d\ln \sigma_1}{d\ln M_1} \,d\ln M_1, \tag{1}
\]

where \(\delta_1\) and \(\delta_2\) represent linear overdensities for collapse at redshifts \(z_1\) and \(z_2\) and \(\sigma = \sigma(M)\). The derivative of this equation under the limit \(z_1 \rightarrow z_2\) yields the number \(N\) of progenitors of mass \(M_1\) that make up a halo of mass \(M_2\) for a small step in redshift space of \(dz_2\). This is written as

\[
\frac{dN}{dM_1} = \frac{1}{M_1} \frac{d f(M_1|M_2)}{d z_2} \frac{M_2}{M_1} \,d z_2 \quad (M_1 < M_2). \tag{2}
\]

Specifying a minimum mass resolution \(M_{\text{res}}\) allows us to compute the mean number of progenitors \(N_p\) with mass \(M_1\) in a mass range \(M_{\text{res}} < M_1 < M_2/2\) via the following equation:

\[
N_p = \int_{M_{\text{res}}}^{M_2/2} \frac{dN}{dM_1} \,dM_1. \tag{3}
\]

The mass fraction \(F\) of the final halo \(M_2\) that is accreted below \(M_{\text{res}}\) can be estimated from

\[
F = \int_0^{M_{\text{res}}} \frac{dN}{dM_1} \frac{M_1}{M_2} \,dM_1. \tag{4}
\]

\(1\) http://star-www.dur.ac.uk/~cole/merger_trees/

### Table 1. The initial parameters for the 12 merger trees.

| \(\eta_{\text{min}}\) | Run | \(f_{\text{seed}}\) | \(f_{\text{unb}}\) (per cent) | \(M_{\text{min}}\) (log \(M_\odot\)) | Mass range (log \(M_\odot\)) |
|---|---|---|---|---|---|
| 0.33 | Major1 | 0.21 | 10.0 | – | 8.0–13.0 |
| 0.33 | Major2 | 0.21 | Random | – | 8.0–13.0 |
| 0.33 | Major3 | Random | 10.0 | – | 8.0–13.0 |
| 0.33 | Major4 | 0.21 | 10.0 | – | 10.0–13.0 |
| 0.33 | Major5 | 0.21 | 10.0 | 10.0 | 10.0–13.0 |
| 0.33 | Major-Keres | 0.21 | 10.0 | – | 8.0–13.0 |
| 0.10 | Minor1 | 0.21 | 10.0 | – | 8.0–13.0 |
| 0.10 | Minor2 | 0.21 | Random | – | 8.0–13.0 |
| 0.10 | Minor3 | Random | 10.0 | – | 8.0–13.0 |
| 0.10 | Minor4 | 0.21 | 10.0 | – | 10.0–13.0 |
| 0.10 | Minor5 | 0.21 | 10.0 | 10.0 | 10.0–13.0 |
| 0.10 | Minor-Keres | 0.21 | 10.0 | – | 8.0–13.0 |

A binary merger tree can then be constructed given \(M_1\) and \(z_2\). We used this technique to construct a set of 12 merger trees, which we outline in Section 3. We have assumed a flat \(\Lambda\) cold dark matter (LCDM) cosmology with \(\Omega_m = 0.044\), \(\Omega_{\text{dm}} = 0.214\), \(\Omega_{\Lambda} = 0.742\), \(\sigma_8 = 0.796\) and \(h = 0.719\), consistent with the Wilkinson Microwave Anisotropy Probe (WMAP) 5-yr cosmology parameters (Komatsu et al. 2009).

## 3 METHOD

As shown in SH09, the amount of gas\(^2\) released by a galaxy merger depends on the mass ratio and the original gas content of the haloes. To incorporate this effect within a merger tree we take the following approach: we seed each halo with a gas fraction \(f_{\text{seed}}\) and assume a galaxy merger with a mass ratio greater than \(\eta_{\text{min}}\) unbinds a fraction of this gas \(f_{\text{unb}}\). We also assume that as the halo grows by diffuse accretion from the IGM, it also accretes gas at the universal gas fraction, increasing the halo gas content. Recent simulations (see Kereš et al. 2005, 2009; Dekel et al. 2009) show that gas does not necessarily heat up to the halo virial temperatures; the majority of the haloes at low \(z\) are only accreting cold gas. To estimate the effect of this multiphase accretion models, we divided the halo gas mass into hot and cold components in accordance with fig. 3 of Kereš et al. (2009). After this partitioning, we follow the same procedure, except now we only unbind gas from the hot gas component. Table 1 outlines the parameters for the 12 experiments.

We designed these 12 experiments to bracket the likely effect that galaxy mergers have on populating the WHIM. A reasonable upper limit is set by allowing even minor mergers (\(\eta_{\text{min}} = 0.1\)) to unbind a fixed fraction \(f_{\text{unb}} = 0.1\) of the progenitor gas mass (run Minor1). Our lower limit is set by seeding only the massive haloes \((M_{\text{halo}} \geq M_{\text{min}} = 10^{10} M_\odot)\) with gas at the universal gas fraction and allowing only major mergers (\(\eta = 0.3\)) to release gas (run Major5). SH09 found that roughly equal-mass mergers can release up to 20 per cent of their initial gas mass, and since the merger rate

\(2\) Since we do not model star formation in our semi-analytic approach, we will use the terms gas and baryons interchangeably.
(per halo per redshift) is relatively flat from $0.3 < \eta < 1.0$ (see fig. 8 in Fakhouri & Ma 2008), we argue that $\eta_{\text{min}} = 0.3$, $f_{\text{sub}} = 0.1$ is a good average scenario. Haloes more massive than $10^{13} M_\odot$, representing groups or clusters of galaxies, cannot be faithfully modelled using this binary galaxy merger mechanism and have been left out.

The input parameters are the final halo mass, $M_2$, the initial redshift, $z_1 = 10$, and the mass resolution, $M_{\text{res}}$. We explore a range of final halo masses from $M_2 = 10^9$–$10^{13} M_\odot$. We use 100 logarithmically spaced mass bins to create a merger tree for a specific $M_1$ at the present epoch. To account for cosmic variance, we run 100 realizations of a fixed halo mass. Thus, overall we create 100 present day halo samples with 100 realizations for a fair sample of possible hierarchical merger histories of structure in the Universe. For each merger tree, we set $M_{\text{res}} = M_2 \times 10^{-3}$. For $10^{13} M_\odot$ haloes, this value of $M_{\text{res}}$ is comparable to the mass of an individual dark matter particle in our numerical simulations (SH09).

We tested the effect of changing $M_{\text{res}}$, $z_1$ and the number of redshift levels and found that our choices produce convergent results for the estimation of the unbound gas.

With these merger histories, we follow all mergers from $z = 10$ to 0 that lead to a halo of mass $M_2$, and eject a fraction of gas from the mergers with mass ratios greater than $\eta_{\text{min}}$. The cumulative sum of the unbound gas produces the total gas released in assembling a particular halo. This yields the fractional gas lost by $z = 0$ on a per halo basis. We repeat this process for 100 realizations, which provides the variance in the gas lost. We can then find the total gas released in generating all haloes in the Universe by convolving with the comoving number density of those haloes at $z = 0$ (Warren et al. 2006). Summing over the final halo masses yields the effect of halo assembly on populating the WHIM.

**4 RESULTS**

Fig. 1 shows the redshift evolution of the cumulative gas mass lost from all haloes in a comoving Mpc$^3$ volume for the run Major1. To generate Fig. 1, we first take the mean of 100 realizations for the unbound gas mass in each redshift step for each halo. This unbound gas mass is added up along the redshift track to yield the cumulative mass at each redshift step and then multiplied by the comoving number density of that particular halo at $z = 0$. This is the cumulative comoving density of the unbound gas for one halo mass. Repeating this process for the 100 final halo masses yields the individual tracks spanning the x-axis. Fig. 1 shows that most massive haloes lose the most gas at all redshifts, in spite of their lower number densities. For example, the current number density in a comoving Mpc$^3$ of a $10^{13} M_\odot$ halo is $10^{6}$ times smaller than for a $10^5 M_\odot$ halo; so the mass density of the $10^8 M_\odot$ halo is an order of magnitude larger than the $10^{13} M_\odot$ halo. This biasing towards higher mass is explained by the hierarchical assembly of haloes—more massive objects today undergo many more mergers in the past. 3

Fig. 2 shows the redshift evolution of the unbound gas mass over the total baryon mass in all the haloes considered in the merger tree. We find that 9 and 24 per cent of the baryons can be ejected by mergers for the Major1 and Minor1 runs, respectively. The mass range of $10^{10}$–$10^{13} M_\odot$ contains 39 and 52 per cent of the total collapsed mass in the Universe, respectively. Thus, the IGM pollution caused by the mergers presented in this paper can only reflect the history of at most half the total matter. If we assume that the same pattern holds true globally, then the fractions presented here (Fig. 2) can be interpreted as normalized by the total baryonic matter density of the Universe. Notice that the fraction of gas lost increases more rapidly with redshift for $\eta_{\text{min}} = 0.1$—this is because 10:1 mergers occur more frequently than 3:1 (e.g. Fakhouri & Ma 2008; Genel et al. 2009).

We can interpret Fig. 2 in the following way: in the Major1 run, the convergence to 10 per cent of the universal gas mass is tantamount to saying that the average halo undergoes one major merger in a Hubble time, since we set major mergers to release 10 per cent of the gas mass. Likewise, the convergence of the Minor1 run can be understood by noticing that minor mergers ($\eta > 0.1$) are two–three times more frequent than major mergers ($\eta > 0.3$; see bottom panel of fig. 8 in Fakhouri & Ma 2008). Thus, the overall unbound density converges to ~20–30 per cent for the Minor1 run.

3 There may be an additional effect from the higher gravitational potential energy ($\alpha c_{\text{vir}}^2$) involved during mergers of massive galaxies (see Johansson, Naab & Ostriker 2009).
In run Major-Keres with multiphase accretion, we find that only ~2 per cent of the gas can be released due to mergers. Since the simulations of SH09 only included hot gas, we chose to unbind only from that phase. In the multiphase scenario, too much gas is in the cold phase and hence, cannot be released during mergers. Even adding a mechanism to heat cold gas by major mergers (equation 4 in Cox et al. 2004) does not convert enough cold gas into a hot phase to be unbound later. If the haloes are only accreting cold gas and this gas cannot be unbound from the haloes before heating it first, then the gas currently populating the WHIM may not have ever fallen into virialized haloes.

In a given merger tree, a fraction of unbound gas is released by mergers between small haloes. To isolate the WHIM fraction (Table 2, column 5) created during the assembly of only the massive galaxies, we run two sets of merger trees with a lower mass limit of $10^9 \ M_{\odot}$. Table 2 shows that most of the unbound gas that is released comes during the formation of massive galaxies. In particular, Major4, with only the massive haloes, produces nearly all of the unbound gas produced in the Major1 run.

Although small haloes merging with massive haloes do not eject any gas, these minor accretion events increase the gas content of the remnant. This could potentially increase the amount of gas released by massive haloes in future mergers. However, if processes like SN feedback evacuate the gas from low-mass haloes, these low-mass haloes cannot increase the gas content of the massive haloes. To mimic this effect, we run two sets of merger trees with a lower mass limit of $10^9 \ M_{\odot}$ and only allow haloes larger than $M_{\text{min}}$ to contain gas. In this scenario (Major5 and Minor5), all small haloes are completely devoid of gas and therefore do not contribute to the gas mass of the big haloes. With this constraint, we find a WHIM fraction of ~3 and 8 per cent for $\eta_{\text{min}} = 0.3$ and 0.1, respectively.

## 5 DISCUSSION

In this paper we show that a significant portion of the WHIM can be generated by gas ejected from galaxies during mergers. Our semi-analytic prescription shows that up to ~25 per cent of the gas (assuming universal gas fraction) in haloes of mass $10^9$–$10^{13} \ M_{\odot}$ can be ejected by mergers. Given an observed gas mass at $z = 0$, it is possible to infer the typical gas mass that was unbound from assembling that halo (column 4, Table 2). For comparison with SN feedback, a quiescent Milky Way type halo with star formation rate of 1–10 $M_{\odot}$ yr$^{-1}$ would unbind $\leq$2 per cent of the gas content (Scannapieco et al. 2008). We also find that multiphase gas accretion drastically reduces the amount of unbound gas from mergers, down to a few per cent of the gas mass. In contrast with previous numerical work involving non-gravitational feedback, where the effects of mass loss are severe in smaller haloes, this merger mechanism unbinds gas preferentially from massive haloes. There is no selective unbinding of gas from dwarf galaxies, in line with observational evidence suggesting that dwarf galaxies are more gas rich and therefore may not have suffered a gas blowout (Kannappan 2004; Geha et al. 2006).

This form of gravitational feedback may even play a larger role in regulating the stellar mass function: Kereš et al. (2009) show that simulated galaxies exhibit a discrepancy with the observed stellar mass function (Bell et al. 2003) for both high- and the low-mass galaxies. They conjecture that the key to solving this discrepancy is through a feedback mechanism that works for haloes $\gtrsim 10^{12} \ M_{\odot}$– akin to our scenario. If the merger-ejection process is very efficient, then the current day haloes may be very gas poor. It is conceivable that the current stellar mass and gas content of the galaxies of the past.

Overall, we find that for our most reasonable scenario, ~15 per cent of the WHIM can be generated through galaxy mergers. If previous work on large-scale gravitational shocks proves correct (Cen & Ostriker 1999; Davé et al. 2001), ~66 per cent of the WHIM can be attributed to gas that may have never fallen into a halo [see Anderson & Bregman (2010) for constraints on hot baryonic halos]. In addition, recent studies have shown that roughly 20 per cent can be produced via non-gravitational feedback, such as SNe and AGN (e.g. Cen & Ostriker 2006). Therefore, with these three mechanisms to populate the WHIM, it may well be true that the baryon budget is balanced.

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