Missing Halo Baryons and Galactic Outflows

Romeel Davé
University of Arizona

Abstract. We present predictions for galactic halo baryon fractions from cosmological hydrodynamic simulations with a well-constrained model for galactic outflows. Without outflows, halos contain roughly the cosmic fraction of baryons, slightly lowered at high masses owing to pressure support from hot gas. The star formation efficiency is large and increases monotonically to low masses, in disagreement with data. With outflows, the baryon fraction is increasingly suppressed in halos to lower masses. A Milky Way-sized halo at $z = 0$ has about 60% of the cosmic fraction of baryons, so “missing” halo baryons have largely been evacuated, rather than existing in some hidden form. Large halos ($\geq 10^{13} M_\odot$) contain 85% of their cosmic share of baryons, which explains the mild missing baryon problem seen in clusters. By comparing results at $z = 3$ and $z = 0$, we show that most of the baryon removal occurs at early epochs in larger halos, while smaller halos lose baryons more recently. Star formation efficiency is maximized in halos of $\sim 10^{13} M_\odot$, dropping significantly to lower masses, which helps reconcile the sub-$L_*$ slope of the observed stellar and halo mass functions. These trends are predominantly driven by differential wind recycling, namely, that wind material takes longer to return to low-mass galaxies than high-mass galaxies. The hot gas content of halos is mostly unaffected by outflows, showing that outflows tend to blow holes and escape rather than deposit their energy into halo gas.

1. Introduction

Everywhere we look, baryons are missing. Globally, observations only account for around half the baryons today (e.g. Fukugita 2004). Simulations indicate that the missing baryons are contained in intergalactic gas at $10^5 < T < 10^7$ K, called the Warm-Hot Intergalactic Medium (WHIM; e.g. Davé et al. 2001). Initially, O vi absorbers seen in quasar spectra were thought to be collisionally-ionized tracers of WHIM gas (Tripp, Savage, & Jenkins 2000). But recent simulations and observations suggest that most intergalactic O vi is actually photo-ionized (Oppenheimer & Davé 2008b, and refs therein), and so the WHIM must be traced using higher ionization lines (e.g. O vii; Nicastro et al. 2005).

Baryons are also missing on galactic scales. Current hierarchical structure formation models predict that baryons do not substantially decouple from dark matter until well inside of halos, hence the expectation is that halos should contain roughly the cosmic fraction of baryons. However, dynamical modeling of the Milky Way’s disk and halo reveals that it contains at best half of its cosmic share of baryons in stars and cold gas (Dehnen & Binney 1998; Sommer-Larsen & Dolgov 2001); the same is true of M31 (Klypin, Zhao, & Somerville 2002). This is the “Missing Halo Baryons” problem. Either a substantial portion
of the $\sim L_*$ galaxies’ halo baryons are in some heretofore hidden form, or else there has been a sizeable exodus of baryons into the intergalactic medium (IGM). Many models have advocated the former possibility, suggesting by analogy with the WHIM that the missing halo gas is in some warm-hot component (e.g. Fukugita & Peebles 2006; Sommer-Larsen 2006), or cold clouds (Maller & Bullock 2004). However, there is little observational evidence for massive coronae of hot gas around typical spirals (Benson et al. 2000; Wang 2007), and furthermore if all halos contained such coronae, this would substantially overpredict the soft X-ray background (Pen 1999; Wu, Fabian, & Nulsen 2001). Meanwhile, the mass in cold clumps as traced by high velocity clouds is unlikely to be sizeable even in optimistic scenarios (Blitz et al. 1999; Sommer-Larsen 2006). In contrast, Silk (2003) developed an analytic model that argued for a substantial fraction of baryons being removed by galactic outflows. In fact, Silk presciently predicted that such outflows could solve a surprisingly wide range of current dilemmas in galaxy formation, which our simulations have largely confirmed.

Clusters also seem to have a missing baryon problem. In a recent census by Gonzalez, Zaritsky, & Zabludoff (2007), baryons make up $\approx 13\%$ of the mass of the cluster, while the latest WMAP-5 results (Hinshaw et al. 2008) favor a cosmic mean value of $\approx 17\%$. This is a small but persistent discrepancy which could have implications for using clusters as probes of precision cosmology.

In these proceedings we examine the baryonic content of galaxy halos in cosmological hydrodynamic simulations with and without galactic outflows. The outflow model implemented in our simulations is unique in that it matches detailed properties of a wide range of outflow-related observables, including IGM enrichment at various epochs (Oppenheimer & Davé 2006, 2008b, 2009), the galaxy mass-metallicity relation (Finlator & Davé 2008), early galaxy luminosity functions (Davé, Finlator, & Oppenheimer 2006), and intragroup gas enrichment and entropy (Davé, Oppenheimer, & Sivanandam 2008). Even though our modeling of outflows is parameterized and heuristic, these successes suggest that it plausibly moves mass, metals, and energy on large scales in a manner consistent with the real Universe.

### 2. Halo Baryon Fractions

We run simulations using our modified version of Gadget-2 (Springel 2005), as described in Oppenheimer & Davé (2008a). The runs here employ $2 \times 256^3$ particles in volumes of $32h^{-1}\text{Mpc}$ and $64h^{-1}\text{Mpc}$, with our WMAP3-concordant d-series cosmology (see Oppenheimer & Davé 2008b). We identify halos using a spherical overdensity algorithm (see Keres et al. 2005), and consider only “resolved” halos with masses $M_h > 128(m_d + m_g)$, where $m_d = (1.6, 12.7) \times 10^8 M_\odot$ and $m_g = (0.34, 2.72) \times 10^8 M_\odot$ are the dark matter and gas particles masses for the $(32, 64) h^{-1}\text{Mpc}$ volumes, respectively. We run two versions of these simulations: One with no winds, and one with our favored momentum-driven (M-D) wind model that matches a range of data as mentioned above. Outflows are implemented in a probabilistic Monte Carlo fashion by giving kicks to gas particles; details are in Oppenheimer & Davé (2008a).

The fraction of baryons within halos are shown in the top panel of Figure 1. In the no-wind case (blue points, upper swath), halos of Milky Way’s size and
Figure 1.  Top: Baryon fraction (relative to cosmic mean) as a function of halo mass, for simulations at $z = 0$ (left panels) and $z = 3$ (right), without winds (blue, upper points) and with momentum-driven winds (green, lower points). Dotted line shows the cosmic baryon fraction assumed in our runs. Middle: Stellar fractions. Bottom: Hot gas ($T > 10^{4.5}K$) fractions. In each panel, the red line shows a running median with $1\sigma$ dispersion, and the two groups of points for each model show results from our $32h^{-1}\text{Mpc}$ and $64h^{-1}\text{Mpc}$ volumes. Outflows drive out substantial amounts of baryons particularly from low-mass systems, which helps regulate star formation to observed level. In large systems most of the mass loss has already occurred by $z = 3$, while in small systems the mass loss occurs later owing to differential wind recycling. Hot gas fractions are a strong function of halo mass, but are not sensitive to outflows. A Milky Way-sized halo today contains about 60% its cosmic share of baryons, of which half is in the form of hot gas, one-third in cool gas, and one-sixth in stars.
below have, as expected, roughly their cosmic share of baryons (shown by the dotted line at $\Omega_b/\Omega_m = 0.044/0.25 = 0.176$). In detail, adiabatic contraction causes the baryon fraction to typically be slightly greater than the cosmic mean. This shows that without any strong feedback, baryons do indeed mostly trace dark matter on halo scales in $\lesssim L_*$ galaxies.

In more massive halos ($M_h \gtrsim 10^{13} M_\odot$), the increasing predominance of hot halo gas (Keres et al. 2008, see also bottom panels of Figure 1) causes pressure support that pushes baryons farther out than the dark matter, and the baryon content is lowered. At the highest masses probed by $z = 0$ ($M_h \sim 10^{14} M_\odot$), this reduction reaches 6%, which is not trivial but still insufficient to explain observed cluster baryon fractions.

Now we consider the M-D wind runs, shown by the lower (green) swath of points. Outflows have a dramatic impact, increasingly so to smaller halo masses. Already by $z = 3$, typical halos ($M_h \sim 10^{11-12} M_\odot$) have had their baryon fraction reduced by $20-30\%$ compared to the cosmic mean. At $z = 3$ there is only a mild trend with halo mass, but by $z = 0$ the trend becomes much stronger: Milky Way-sized halos ($M_h \sim 10^{12} M_\odot$) have lost roughly 40% of their baryons, while the smallest halos we probe at $M_h \sim 10^{10.5} M_\odot$ have lost 60%. This indicates that missing halo baryons have mostly been ejected by outflows.

Outflows have a noticeable impact on large halos as well. Davé, Oppenheimer, & Sivanandam (2008) showed that outflows add substantial entropy on poor group scales, and this translates into increased pressure support over the no-wind case. With outflows, the most massive ($M_h \gtrsim 10^{14} M_\odot$) halos now contain only 85% of their cosmic share of baryons, and the trend is essentially flat with halo mass. This value is in better agreement with observational estimates (Vikhlinin et al. 2006; Gonzalez, Zaritsky, & Zabludoff 2007).

The falling baryon fraction in low-mass halos is a consequence of wind recycling in our outflow model, i.e. the re-accretion of previously ejected wind material. In Oppenheimer & Davé (2008a), we found that small galaxies push their winds out farther relative to large galaxies (owing primarily to the fact that they reside in less dense surroundings), and as a result the time for winds to be re-accreted onto small systems is longer. At early epochs, recycling is relatively unimportant, because there hasn’t been sufficient time to permit substantial re-accretion. The weak trend seen at $z = 3$ owes to the fact that our mass loss rate scales inversely with velocity dispersion in our momentum-driven wind scalings. By $z = 0$, however, the longer recycling times in smaller systems results in much more cumulative mass loss from small halos relative to larger halos. Hence differential wind recycling is the dominant driver in establishing the baryon fraction trends with halo mass. As we will see next, it is also critical for regulating the star formation efficiency in smaller systems.

### 3. Stellar Baryon Fractions

We now separate baryons within each halo into three phases: Stars, cool gas ($T < 10^{4.5} \text{K}$), and hot gas ($T > 10^{4.5} \text{K}$). Star-forming gas is included in cool gas. The middle and bottom panels of Figure 1 show the baryon fractions in stars and hot gas, respectively; the remainder is in cool gas (not shown). In this section we examine stellar baryon fractions.
With no outflows, there is a serious overcooling problem: Star formation is far too efficient. In sub-$L_\ast$ halos, the fraction of baryons in stars approaches 90%, while observed small galaxies have stellar fractions under 10%. Moreover, the trend is wrong: with no winds, smaller galaxies have a higher baryon fraction in stars, while the shallow slope of the stellar mass function below $L_\ast$ relative to the halo mass function indicates that the stellar mass fraction should be lower in small halos. At group scales, the stellar baryon fraction is down to 25% of the cosmic mean, but that is still too high compared to data as pointed out in Davé, Oppenheimer, & Sivanandam (2008). Of course, these results are not surprising, as it is well known that outflows, particularly at early epochs, are required to suppress overcooling (e.g. Davé, Finlator, & Oppenheimer 2006).

With outflows, the situation improves dramatically. Stellar fractions are reduced to a maximum of $\approx 20\%$ for $\sim 10^{13} M_\odot$ halos, falling to either smaller or larger halos. A Milky Way-sized halo now has a 12% stellar fraction (relative to $\Omega_b$), which is in general agreement with observations of comparable disk galaxies (Hammer et al. 2007). The stellar fraction drops towards lower halo masses, suggesting a flatter stellar mass function compared to the halo mass function, as observed. The slope of the $z = 0$ fit (red line) is approximately $d\log f_\ast/d\log M_h \approx 0.5$ for $M_h < 5 \times 10^{12} M_\odot$, which when combined with the halo mass function slope of $\approx -2$, yields a stellar mass function slope of $\approx -1.5$. This is in general agreement with observations of the sub-$L_\ast$ stellar mass function slope (Baldry, Glazebrook, & Driver 2008), though still too steep; in fact, the faint-end slope turns out to be even shallower, as will be shown in a forthcoming paper. Note that the stellar fraction slope at $z = 3$ is less steep, reflecting the shallower slope in the overall halo baryon fraction (top right panel). Our models naturally yield a flattening of the faint end slope with time.

The qualitative trend of the star formation efficiency having a maximum at some mass and dropping fairly rapidly to low masses, along with the faint end slope evolution, is a direct consequence of differential wind recycling. Without it, the star formation efficiency would continue to increase to small masses, as in the no-wind case. Hence models of galaxy formation must not only include outflows, but must also track the dynamics of wind material on its journey through the IGM to properly capture its impact on galaxy evolution.

4. Hot Gas Baryon Fractions

Turning to the hot gas ($T > 30,000$ K) baryon fractions (bottom panels of Figure 1), there is a strong trend of hot gas fraction increasing with halo mass, which is mostly independent of redshift and whether or not outflows are included. In the no-wind case, the hot gas fraction exceeds the stellar fraction (which comprises the vast majority of condensed baryons) at $z = 0$ for $M_h \gtrsim 10^{12.5} M_\odot$. This transition occurs at a somewhat larger mass than found in Keres et al. (2008), likely because our runs include metal-line cooling.

With outflows, the fraction of halo gas in hot form is more substantial, exceeding the stellar fraction in the outflow case at all masses probed here. This is due to the suppression of star formation, rather than an increase in the amount of hot gas. Relative to the baryon fraction, the hot gas fraction is about one-third of all halo baryons at the smallest masses probed, and increases
to three-fourths or more for $M_h \gtrsim 10^{13} M_\odot$. This indicates that there is still a substantial reservoir of baryons in a difficult-to-detect phase within typical galaxies, and indeed X-ray observations do indicate a warm-hot corona around a nearby spiral galaxy [Pedersen et al. 2006]. However, the amount of hot gas we predict is still a factor of two to three smaller than in models that place the majority of missing halo baryons into this phase. This roughly translates into up to an order of magnitude reduction in the predicted X-ray flux (as compared to e.g. Benson et al. 2000). Hence the typical non-detection of X-ray halos around spiral galaxies should not be surprising, but deeper observations with future X-ray telescopes should uncover this phase more ubiquitously.

It is noteworthy that our outflows do not significantly increase the amount of hot gas into halos (as seen by comparing to the no-wind case). Winds in our models tend to escape halos without depositing a significant amount of energy along the way via shocks. This is contrary to typical assumptions in analytic or semi-analytic models of outflows (e.g. Dekel & Silk 1986), and simply reflects the fact that in realistic three-dimensional models outflows prefer to blow holes rather than share their energy with ambient gas. This is also consistent with X-ray observations of hot gas around galaxies that indicate they are radiating a small fraction of the supernova energy input (e.g. Wang 2007). Another factor is that outflows are typically quite enriched, so that the gas cooling times are short, and hence even if outflow material is heated it condenses out quickly. At low-$z$ this results in a “halo fountain” that may be the origin of compact high velocity clouds (Wang 2007; Oppenheimer & Davé 2008a).

5. Summary

We have examined halo baryon fraction in cosmological hydrodynamic simulations, comparing models with and without galactic outflows. Our outflow model is heuristic, but is well-constrained to match a variety of galaxy and IGM observations at a range of epochs. We find that these same outflows may help resolve some puzzles regarding the baryonic content of galactic halos.

For low mass halos, outflows remove a significant portion of halo baryons by $z = 0$. The fraction of ejected baryons increases sharply to lower masses, so that $10^{12} M_\odot$ halos have lost 40% of their baryons, and $10^{10.5} M_\odot$ halos 60%. The trend is not as pronounced at $z = 3$, showing that the longer wind recycling times in small galaxies (i.e. differential wind recycling) plays a critical role in suppressing the baryon fractions in small halos between $z = 3 \rightarrow 0$. This may explain why the faint-end slope of the luminosity function becomes shallower with time. By today, this produces a peak in star formation efficiency at $\sim 10^{12.5-13} M_\odot$, above and below which the efficiency falls. Meanwhile, hot gas fractions are mostly unaffected by outflows, showing that outflows do not deposit much of their energy into halo gas, instead preferring to blow holes and escape. A Milky Way-sized halo today has about 60% of its cosmic share of baryons, half of which are in hot gas, one-third in cool gas, and the remainder in stars.

For high mass halos ($M_h \gtrsim 10^{13} M_\odot$), there is a mild suppression of baryon fractions owing to larger pressure support from an increasingly substantial hot gaseous halo. Without winds, the suppression is fairly small ($\approx 5\%$). In our outflow run, conversely, the suppression is much more substantial, $\approx 15\%$, inde-
pendent of mass, which agrees better with data. This demonstrates that outflows impact even massive halos today. The key is that most of the ejection occurs at early epochs, when those halos were much smaller.

Our implementation of outflows is primarily constrained to match IGM enrichment at $z \sim 2 - 4$ (e.g., Oppenheimer & Davé 2006). The fact that this model naturally yields observationally-consistent results for halo baryon fractions at $z \sim 0$ is highly encouraging, and represents another significant success for our outflow model based on momentum-driven wind dealings. It may be that we are approaching a heuristic understanding of how outflows operate on extragalactic scales, even though the detailed mechanisms by which outflows are driven out of galaxies remain unclear.

Acknowledgments. RD thanks Shardha Jogee and the organizing committee for an excellent meeting. The simulations were run on UA’s SGI cluster.

References
Baldry, I. K., Glazebrook, K., Driver, S. P. 2008, MNRAS, 388, 945
Benson, A. J., Bower, R. G., Frenk, C. S., White, S. D. M. 2000, MNRAS, 314, 557
Blitz, L, Spergel, D. N., Teuben, P. J., Hartmann, D., Burton, B. 1999, ApJ, 514, 818
Davé, R., et al. 2001, ApJ, 552, 473
Davé, R., Finlator, K., Oppenheimer, B. D. 2006, 370, 273
Davé, R., Oppenheimer, B. D., Sivanandam, S. 2008, MNRAS, 391, 110
Dehnen, W. & Binney, J. 1998, MNRAS, 294, 429
Dekel, A. & Silk, J. 1986, ApJ, 303, 39
Finlator, K. & Davé, R. 2008, MNRAS, 385, 2181
Fukugita, M. 2004, in proc. IAU Symp. 220, eds. S. D. Ryder et al., San Francisco: ASP, p.227
Fukugita, M. & Peebles, P. J. E. 2006, ApJ, 639, 590
Gonzalez, A. H., Zaritsky, D., Zabludoff, A. I. 2007, ApJ, 666, 147
Hammer, F., Puech, M., Chemin, L., Flores, H., Lehnert, M. D. 2007, ApJ, 662, 322
Hinshaw, G. et al. 2008, arXiv:0803.0732
Keres, D., Katz, N., Weinberg, D. H., Davé, R. 2005, MNRAS, 363, 2
Keres, D., Katz, N., Fardal, M., Davé, R., Weinberg, D. H. 2008, MNRAS, submitted, arXiv:0809:1430
Klypin, A., Zhao, H., Somerville, R. S. 2002, ApJ, 573, 597
Maller, A. & Bullock, J. 2004, MNRAS, 355, 694
Nicastro, F. et al. 2005, Nature, 433, 495
Oppenheimer, B. D., Davé, R. 2006, MNRAS, 373, 1265
Oppenheimer, B. D., Davé, R. 2008a, MNRAS, 387, 577
Oppenheimer, B. D., Davé, R. 2008b, MNRAS, submitted, arXiv:0808.2866
Oppenheimer, B. D., Davé, R., Finlator, K. 2009, MNRAS, submitted, arXiv:0901.0286
Pedersen, K., Rasmussen, J., Sommer-Larsen, J., Toft, S., Benson, A. J., Bower, R. G. 2006, NewA, 11, 465
Pen, U.-L. 1999, ApJ, 510, L1
Silk, J. 2003, MNRAS, 343, 249
Sommer-Larsen, J. & Dolgov, A. 2001, ApJ, 551, 608
Sommer-Larsen, J. 2006, ApJ, 644, L1
Springel, V. 2005, MNRAS, 364, 1105
Tripp, T. M., Savage, B. D., Jenkins, E. B. 2000, ApJ, 534, L1
Vikhlinin, A. et al. 2006, ApJ, 640, 691
Wang, Q. D. 2007, in proc. “Chemodynamics: from first stars to local galaxies”, eds. E. Ensselme et al., EAS v.24, p.59
Wu, K. K. S., Fabian, A. C., Nulsen, P. E. J. 2001, MNRAS, 324, 95