Revisiting the Baryon Fractions of Galaxy Clusters: A Comparison with WMAP 3-year Results

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ABSTRACT

The baryonic mass fraction ($\Omega_b/\Omega_m$) can be sensitively constrained using X-ray observations of galaxy clusters. In this paper, we compare the baryonic mass fraction inferred from measurements of the cosmic microwave background with the gas mass fractions ($f_{\text{gas}}$) of a sample of 19 clusters taken from the recent literature. In systems cooler than 4 keV, $f_{\text{gas}}$ declines as the system temperature decreases. However, in higher temperature systems, $f_{\text{gas}}$ converges to $(0.12 \pm 0.02)(h/0.72)^{-1.5}$, where the uncertainty reflects the systematic variations between clusters and the dependence on radius beyond $r_{500}$. This is significantly lower than the maximum-likelihood value of the baryon fraction from the recently released WMAP 3-year results. We investigate possible reasons for this discrepancy, including the effects of radiative cooling and non-gravitational heating, and conclude that the most likely solution is that $\Omega_m = 0.28-0.39$, higher than the best-fit WMAP value, but consistent at the 2σ level. Degeneracies within the WMAP data require that $\sigma_8$ must also be greater than the maximum likelihood value for consistency between the data sets.

Key words: cosmology: theory — galaxies: clusters: general — X-rays: galaxies: clusters

1 INTRODUCTION

For over a decade now cluster gas mass fractions as inferred from X-ray observations have been used as a probe of the present-day universal ratio of baryon to total matter densities, $\Omega_b/\Omega_m$ (e.g., White et al. 1993; David et al. 1995; Evrard 1997; Mohr et al. 1999; Rousset et al. 2000; Allen et al. 2002; Lin et al. 2003; Ettori et al. 2003). Supplementing these gas mass fractions with constraints on $\Omega_b$ from, e.g., cosmic microwave background (CMB) measurements or a combination of Big Bang Nucleosynthesis (BBN) predictions and D/H measurements from high redshift quasars, therefore allows one to measure the total matter density $\Omega_m$. The reliability of this test rests on the assumption that clusters have been able to retain the original baryon inventory assigned to them in the early universe. So-called “non-radiative” cosmological simulations, which include a hydrodynamic treatment of the baryons but neglect sources or sinks such as radiative cooling, star formation, and feedback, indeed indicate that clusters retain nearly all their baryons until the present day (e.g., Frenk et al. 1999; Kay et al. 2004; Crain et al. 2006). The same is generally true for simulations with cooling and feedback. Although the fraction of baryons in the hot phase depends strongly on the model, most recent simulations predict a mild increase in the hot gas fraction with cluster mass, and little evolution with redshift (e.g., Tornatore et al. 2003; Kravtsov et al. 2005; Ettori et al. 2006).

The high-quality data obtained from the Chandra and XMM-Newton telescopes allow us to probe both the surface brightness and temperature profiles of clusters, out to sufficiently large radii that both the statistical and systematic observational uncertainties on the gas mass fraction are substantially improved. These profiles can be used to yield the three-dimensional gas density and temperature distributions of the ICM which, in turn, can provide the total mass profiles of clusters under the theoretically-motivated (e.g., Evrard et al. 1996) and observationally supported (e.g., McCarthy et al. 2006) assumption that the ICM is in hydrostatic equilibrium (HSE) within the cluster’s potential well. In this paper we analyse the best literature data in a homogeneous way, and compare the results with the universal baryon fraction inferred from the recently released WMAP 3-year data (Spergel et al. 2006).

Unless otherwise stated, we assume a ΛCDM cosmology with $h = 0.72$. 
2 CLUSTER GAS FRACTIONS

We select high quality data from a few recent studies in the literature where the mass profiles have been computed in this way. Vikhlinin et al. (2006), hereafter V06, have measured the gas and total mass profiles for a sample 13 relaxed “cool core” observed with Chandra. From this sample, we select all but two clusters\(^1\). In addition to the above, we also select a sample of 10 relaxed “cool core” clusters observed with XMM-Newton for which Pointecouteau et al. (2005), Arnaud et al. (2005) and Pratt et al. (2006a) (hereafter collectively referred to as PAP) have computed gas and total mass profiles. Therefore, in total we have compiled a sample of 21 sets of mass profiles from 19 different clusters (i.e., the samples have two clusters in common).

Both V06 and PAP computed the gas and total mass profiles of their clusters in a similar manner, by fitting parametric forms of the gas density and (3D) temperature profiles of the ICM (see eqns. 3 and 6 of V06 and Appendix A of Pratt et al. 2006a) to the observed, projected surface brightness and temperature profiles. The purpose of these parametric models is to produce a smooth description of the data and hence reduce the noise in the spatial derivatives; the exact form of the models is irrelevant as long as they fit the data well. Note that the assumption of smooth gas in HSE can lead to a small overestimate of the baryon fraction (Mathiesen et al. 1999; Mohr et al. 1999; Rasia et al. 2006; Nagai et al. 2006), which strengthens our conclusions.

We use the parametric models and associated best-fit parameters listed in V06 and PAP to reconstruct the observed mass profiles. In both studies the total mass distributions were fitted with the Navarro, Frenk & White (1997, NFW) profile derived from cosmological dark matter simulations. Both V06 and PAP demonstrate that the NFW profile fits their data exceptionally well, with an inferred 4.5 keV (red lines) have systematically lower values for mass. In particular, systems with mean temperatures below and above 4.5 keV, respectively. The magenta line represents PAP’s fit to A1413. The error bars give an indication of the typical statistical measurement uncertainty. The vertical dotted line indicates an overdensity of 500 (i.e., corresponds to \(r_{500}\)). Finally, the shaded cyan region corresponds to the 68% confidence region for \(f_b/A_{\Omega_m}\) from WMAP, while the long dashed line shows the best fit value (Spergel et al. 2006).

Presented in Figure 1 is a comparison of the observed integrated gas mass fractions [i.e., \(f_{\text{gas}} \equiv M_{\text{gas}}(< \Delta_s)/M_{\text{tot}}(< \Delta_s)\)] as a function of overdensity (\(\Delta_s\)) with WMAP 3-year constraints on the universal baryon fraction \(\Omega_b/\Omega_m\) (assuming a flat power-law \(\Lambda\)CDM cosmology). Solid and dashed lines represent fits to the Chandra data of V06 and XMM-Newton data of PAP, respectively. Red and black lines represent systems with mean spectral temperatures below and above 4.5 keV, respectively. The magenta line represents PAP’s fit to A1413. Error bars give an indication of the typical statistical measurement uncertainty. The vertical dotted line indicates an overdensity of 500 (i.e., corresponds to \(r_{500}\)). Finally, the shaded cyan region corresponds to the 68% confidence region for \(f_b/A_{\Omega_m}\) from WMAP, while the long dashed line shows the best fit value (Spergel et al. 2006).

\[ \Delta_s \equiv 3M_{\text{tot}}(< r)/\left[4\pi r^3\rho_{\text{crit}}(z)\right] \]

In general, the clusters all show a mildly rising gas fraction with decreasing overdensity. However, there is considerable scatter in the gas fraction at fixed overdensity that is worth exploring. Indeed, V06 generally find temperature profiles that decline relatively rapidly with radius, dropping by roughly a factor of 2 from the peak (at \(r \approx 0.1 - 0.2r_{500}\)) to 0.5\(r_{200}\) (see also Vikhlinin et al. 2005), while PAP find a much more gradual decline, with some clusters showing approximate isothermality. Through the equation of HSE, a flatter temperature gradient translates into a reduced normalisation of the total mass profile and hence an increased gas mass fraction. While it would be useful to sort out the exact nature of the temperature discrepancy\(^2\), we point out that the typical level of difference between the two is relatively small. The one exception to this appears to be A1413, which was observed by both V06 and PAP. Within \(r_{500}\), V06 find a total mass that is roughly 50% larger than that found by PAP. Increasing the total mass of A1413 by this factor would bring it more in line with the other systems studied by PAP. However, we note that good agreement between PAP and V06 is found for A1991, the only other system in common between the two samples.

Fig. 1 also shows that the gas fraction depends on system temperature, which presumably reflects total system mass. In particular, systems with mean temperatures below 4.5 keV (red lines) have systematically lower values for \(f_{\text{gas}}\) within virtually all overdensities compared with hot-

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\(^{1}\) We exclude A2390, which V06 have demonstrated to be highly asymmetric owing to the presence of a set of large X-ray cavities nearly 400 kpc in diameter, and the low-temperature system USGC S152, for which V06 do not provide enough information to reconstruct its mass profile.

\(^{2}\) It now appears that the discrepancy between temperature profiles derived with Chandra and those with XMM-Newton may be nearly resolved. Using a larger sample of clusters observed with XMM-Newton and an improved model for background subtraction, Pratt et al. (2006b) now find steeper temperature declines at large radii which are quite similar to those of V06 (G. W. Pratt, private communication). See also Vikhlinin et al. (2005).
3 IMPLICATIONS

In cosmological simulations the baryon fraction within $r_{500}$ has converged to 90 – 95% of the universal value in the case of non-radiative simulations (e.g., Frenk et al. 1999; Kay et al. 2004; Crain et al. 2006) and slightly higher than this when radiative cooling and star formation is included (e.g., Kravtsov et al. 2005; Ettori et al. 2006). It is only possible to drive a substantial fraction of the baryons beyond $r_{500}$ if the energy input from non-gravitational heating (such as AGN powered jets and bubbles; e.g., Churazov et al. 2002) is comparable to the binding energy of the cluster gas (we quantify the energy requirement in §3.2). In the absence of such high levels non-gravitational heating, the baryon fractions derived at $r_{500}$ should be representative of the universal value.

Independent measurements of the universal baryon fraction $\Omega_b/\Omega_m$ can be derived from the power spectrum of CMB anisotropies. In Figs. 1 and 2 we show the value of $\Omega_b/\Omega_m$ constrained by the WMAP 3-year data (Spergel et al. 2006). From Fig. 1 it is immediately apparent that, with the exception of A1413, the observational gas mass estimates do not achieve consistency with the WMAP measurements of the baryon fraction within any (observable) overdensity.

This is true despite the fact that the XMM-Newton data extend out to nearly $r_{500}$ (note that, typically, $r_{500} \sim 1$ Mpc) and slightly beyond this in the case of Chandra. At the lowest observable overdensity (largest radii), the data indicate a gas mass fraction that is roughly 40% lower than $\Omega_b/\Omega_m$ inferred from WMAP 3-year data. Fig. 2 demonstrates that the observed gas mass fractions at $r_{500}$ have converged for systems above $\sim 4$ keV, and still lie well below the WMAP 3-year constraints. We now examine the possible origins of this sizeable discrepancy. For ease of discussion, we break up the possible solutions into three broad categories.

3.1 Stars and cool baryons

X-ray data by itself constrains only the fraction of a cluster’s mass in the form of hot ($T > 10^6$ K) gas. A proper comparison to the universal WMAP baryon fraction therefore requires that we take into account the fraction of cluster’s baryons locked up in cool gas (that doesn’t emit X-rays), stars and baryonic cold dark matter. If clusters manage to significantly cool $\approx 40\%$ of their baryons this would potentially resolve the discrepancy described above. Indeed, cosmological simulations that take into account the effects of radiative cooling and star formation demonstrate that clusters can potentially cool out such large quantities of their baryons (e.g., Davé et al. 2002; Kravtsov et al. 2005). But such simulations are at odds with near-infrared observations of clusters, which typically indicate that the total (resolved) stellar mass is at most 5-10% of the ICM gas mass in hot ($> 4$ keV) clusters and only slightly higher than this in cooler systems (e.g., Balogh et al. 2001; Lin et al. 2003). Recent deep optical observations limit the contribution of diffuse intracluster light to between $\sim 10 – 30\%$ of the total stellar luminosity (e.g., Gonzalez et al. 2005; Zibetti et al. 2005). Low mass stars and brown dwarfs (or “rocks”) are also likely to be a significant, undetected component of the mass budget, but there is no strong evidence that they are more abundant than expected from standard initial mass functions used to extrapolate the observed stellar mass functions (Fuchs, Jähnich & Flynn 1998; Gizis et al. 2000; Lucas et al. 2005; Levine et al. 2006). As for cool ($T < 10^{2.5}$ K) diffuse baryons, radio, infrared, and ultraviolet surveys for atomic, molecular, and ionised gas (respectively) limit their contribution to less than a percent or so of the hot X-ray-
emitting ICM (e.g., O’Dea et al. 1998; Donahue et al. 2000; Edge 2001; Edge & Frayer 2003; Bregman et al. 2006).

It therefore appears that the stellar/cool baryon contribution to the total cluster baryon budget is roughly a factor of three too small to account for the cluster vs. CMB discrepancy.

3.2 Non-gravitational heating

As discussed above, the small fraction of cooled baryons observed, relative to the predictions of cooling-only simulations, implies that some form of non-gravitational heating (“feedback”) is at work in the ICM. Without significant feedback to prevent this overcooling, theoretical models are unable to account for the observed cut-off of the galaxy luminosity function at the bright end or the fact that BCGs are, by and large, “red and dead” (e.g., Benson et al. 2003; Bower et al. 2006), nor would it be possible to explain the lack of X-ray emission from intracluster gas with temperatures below about 1 keV (e.g., Peterson et al. 2003). Non-gravitational heating also appears to be necessary to account for the X-ray scaling properties of clusters (e.g., Kaiser 1991; Evrard & Henry 1991; Babul et al. 2002; Voit et al. 2002; McCarthy et al. 2004). Injecting thermal energy into the ICM will cause the ICM to expand and therefore will reduce the gas mass fraction within a given radius. Can this heating explain the discrepancy between cluster and CMB measurements?

To test this, we have computed the bulk energy required to transform clusters with the universal baryon fraction (all in hot gas) into the observed systems. For our baseline (unmodified) model clusters, we assume the gas traces the total matter at all radii and, therefore, within any radius the integrated gas mass fraction is always the best-fit WMAP 3-year value $\Omega_b/\Omega_m = 0.176$. The total mass profiles (which are dominated by dark matter) are assumed to be the same as those measured by V06 and PAP, thus we construct a baseline model cluster for each of the observed systems. The temperature profiles are determined by placing the gas in HSE. Calculating the total energy of the gas in these systems (i.e., the summation of the total internal and potential energies) is then straightforward. For the observed systems, we extrapolate the gas and total density profiles beyond the maximum radius to which they can be observed, until the integrated gas mass fraction is the universal ratio. We assume the total density profiles continue to follow the NFW form fit by V06 and PAP. We try various different power-law extrapolations for the gas density profiles with plausible indices ranging from 0 to −2.5. We find that the minimum energy required to convert the baseline models into the observed systems occurs when the gas density is constant with radius outside the maximum observable radius. This configuration is perhaps unlikely, but it does provide a useful lower limit to the amount of heating required. Like the baseline models, we place the gas in the observed systems in HSE. Reassuringly, we verify that the resulting temperature profiles are in good agreement with the observed profiles. The total (minimum) energy required to heat the ICM is just the difference of the total energy of the observed and unmodified baseline systems.

For hot ($T_{\text{spec}} > 4$ keV) clusters, we find that a substantial amount of energy is required, ranging between $6 - 45 \times 10^{52}$ ergs with a mean of $\approx 2.2 \times 10^{52}$ ergs (assuming $p_{\text{gas}}$ is constant outside the maximum observable radius - i.e., the minimum required energy). It is interesting to compare this minimum energy estimate with the energy that can potentially be deposited by AGN, the most powerful source of non-gravitational heating we know of in clusters of galaxies. We estimate the amount of AGN energy available to be tapped as follows. First, we convert Lin et al. (2003)’s observed relationship between stellar mass fraction and total mass within $r_{500}$ (see equation 10 of that study) into a stellar—total mass relation [i.e., $M_{\text{stellar}}(r_{500}) - M_{500}$] assuming a gas mass fraction of 0.12 within $r_{500}$ (see Fig. 1). This relation can be converted into a relationship between the total mass in black holes within $r_{500}$ by (optimistically) assuming that the entire stellar mass is contained in bulges and adopting the black hole—bulge mass ($M_{\text{BH}} - M_{\text{bulge}}$) relation of Häring & Rix (2004). This leads to the following $M_{\text{BH}}(r_{500}) - M_{500}$ relation:

$$
\log_{10}[M_{\text{BH}}(r_{500}) / M_\odot] = 1.12 \log_{10} \left( \frac{f_{\text{gas}}(r_{500})}{0.12} \right) + 0.84 \log_{10} \left( \frac{M_{500}}{5 \times 10^{14} M_\odot} \right) + 10.229
$$

Finally, this is converted into an estimate of amount of AGN energy available via $E_{\text{AGN}} = cM_{\text{BH}}(r_{500})^2 c^2$.

In Figure 3, we present a comparison of the minimum specific energy required to resolve the cluster vs. CMB discrepancy with the energy available to be tapped in black holes. In order to explain the most massive systems, we calculate that a minimum energy of $\approx 10$ keV per particle is required. If one adopts an efficiency of $\epsilon = 0.1$, which is approximately the efficiency predicted by standard radiatively efficient accretion disk models (e.g., Shakura & Sunyaev 1973), there is potentially just enough energy available in black holes distributed throughout $r_{500}$ to account for the observed gas mass fractions. (We use the term ‘potentially’ since we remind the reader that we have calculated the minimum energy required and furthermore have made optimistic assumptions about the mass of black holes available to heat the ICM.) However, modelling of AGN-blown X-ray cavities (or bubbles) suggest the typical cluster black hole efficiency is much lower than 0.1. The most energetic AGN outbursts known, in Hercules A (Nulsen et al. 2005) and MS0735.6+7421 (McNamara et al. 2005), have mean powers of $\approx 1.6 - 1.7 \times 10^{46}$ ergs s$^{-1}$. The typical age of such outbursts is $\approx 100$ Myr, corresponding to a total energy of few times $10^{45}$ ergs or a specific energy of a few tenths of a keV per particle. This falls nearly two orders of magnitude short of the required minimum to reduce a massive cluster’s baryon fraction from the universal WMAP value to the observed fraction. Therefore, even if a typical cluster

Note that we also extrapolate the baseline models to this radius to ensure that both the baseline and observed systems have the same integrated gas and total masses.

4 We have slightly adjusted this relation by scaling up the total masses of Lin et al. by 1.26 to account for the normalisation difference between the ASCA total mass-temperature relation assumed by Lin et al. and the more accurate Chandra relation measured by V06.
experiences 10 such powerful outbursts over its lifetime (say, once per Gyr over 10 Gyr) the energy injected into the ICM still falls short of the minimum required energy by up to an order of magnitude.

We therefore conclude that AGN heating is a highly implausible, but perhaps not impossible, solution to the cluster vs. CMB discrepancy. In addition to the exceptionally large energy requirements, we point out that the heating must be distributed in just such a way as to explain the convergence trend in Fig. 2 and the fact that the ICM properties at large radii in massive clusters follow the standard (gravitational) self-similar scalings (McCarthy et al. 2006).

3.3 Different cosmological parameters: \( \Omega_m \) and \( h \)

The observed gas fractions are proportional to \( h^{-1.5} \), while the WMAP constraint is independent of \( h \). Thus, adopting a lower value of \( h \approx 0.55 \) would bring these two results into agreement. Indeed, this is why similar analyses by Roussel et al. (2000) and Sadat et al. (2005), who adopt \( h = 0.5 \), find higher gas fractions than we have shown here. However, the large body of independent evidence in favour of \( h > 0.6 \) (e.g. York et al. 2005; Jones et al. 2005; Riess et al. 2005; Ngeow & Kanbur 2006) makes this solution seem unlikely.

Instead, we will assume \( h = 0.72 \) and adopt the latest QSO constraints on the baryon density \( \Omega_b h^2 = 0.0213 \pm 0.0013 \pm 0.0004 \); see O'Meara et al. 2006). Then for an observed gas mass fraction of 11-13% (see Fig. 1), allowing for 6-13% of cluster's baryons to be in the form of stars and cool gas (see §3.1), and taking in account that \( f_{\text{gas}} \) measurements are expected to be biased high by \( \approx 10\% \) because of the assumption of HSE (e.g., Nagai et al. 2006), we find \( \Omega_m = 0.28-0.39 \). This is larger than the best-fit WMAP 3-year value of \( \Omega_m = 0.238 \pm 0.03 \), but is in good agreement with previous X-ray analyses (e.g., Allen et al. 2002; Lin et al. 2003; Ettori et al. 2003), Sloan Digital Sky Survey (SDSS) measurements of the Lyman alpha forest power spectrum (Viel & Haehnelt 2005), the baryon acoustic peak of luminous red galaxies (Eisenstein et al. 2005), and the power spectrum of galaxies (Tegmark et al. 2004). We also note that combining WMAP 3-year joint constraints on \( \Omega_m h^2 \) and \( \sigma_8 \) (which are degenerate, see below) with weak lensing cosmic shear measurements (Hoekstra et al. 2006) results in an increased best-fit value for \( \Omega_m \) that is in good agreement with our results (see Fig. 7 or Spergel et al. 2006). Li et al. (2006) have also recently reported that the “low” value of \( \Omega_m \) reported by Spergel et al. (2006) is in discord with the number of observed strong lensing giant arcs, however a fiducial flat model with \( \Omega_m = 0.3 \) and \( \sigma_8 = 0.9 \) is able to match the lensing data.

Thus, while \( \Omega_m \) in the range 0.28-0.39 is marginally inconsistent with the WMAP 3-year joint constraints, this offers an appealing explanation for the relatively small gas mass fraction seen in clusters. It should be noted, however, that the WMAP constraints on \( \Omega_m \) and \( \sigma_8 \) are strongly degenerate. Thus the cluster gas fraction data also imply that \( \sigma_8 \) lies in the range 0.85—1.2, somewhat above the best-fit value derived from WMAP alone \((0.74^{+0.05}_{-0.06})\). This has important implications for the abundance of collapsed objects prior to re-ionisation (Reed et al. 2006).

4 CONCLUSIONS

Recent, good quality observations of massive clusters with Chandra and XMM-Newton put strong observational constraints on the gas mass fraction in massive clusters at large radius. In many cases the new data allow the fraction to be constrained out to \( r_{200} \) (the radius at which the cluster density contrast is 500). Simulations of clusters suggest that the cluster gas fraction at this radius should closely reflect the average baryon mass fraction in the universe as a whole.

We find \( f_{\text{gas}} = (0.12 \pm 0.02) \cdot (h/0.72)^{-1.5} \), where the uncertainty reflects the systematic variations between clusters and the residual dependence on radius. This is lower than the best fit to the WMAP 3-year result of \( f_{\text{gas}} = 0.176 \pm 0.02 \).

We consider whether the discrepancy could be due to a large fraction of the cluster gas cooling to form stars and cold gas clouds, or whether it could be due to strong non-gravitational heating transporting \( \sim 30\% \) of the cluster gas outside \( r_{200} \). Observational limits on the stellar and cold gas content of clusters appear to rule out the first possibility. In order to investigate the second, we compute the energy budget required to rearrange the cluster gas. The energy required significantly exceeds the plausible energy input from black holes, unless their mass accretion history is always associated with efficient jet production.

The most likely explanation is that \( \Omega_m \) lies in the range 0.28—0.39, as we would infer by combining the cluster gas.
fractions with recent estimate of the baryon density from BBN and D/H measurements. Such a relatively high $\Omega_m$ lies slightly above the 68 per cent confidence limits from WMAP, but is consistent with the current data at the 2$\sigma$ level. We note, however, that since the measurements of $\Omega_m$ $WMAP$ lies slightly above the 68 per cent confidence limits from $^{6}$I. G. McCarthy et al. BBN and D/H measurements. Such a relatively high $\Omega_m$ fractions with recent estimate of the baryon density from $\sigma_8$. We note, however, that since the measurements of $\Omega_m$ and $\sigma_8$ are highly correlated in the WMAP analysis, this means that $\sigma_8$ is also likely to be higher than the formal best-fit value of 0.74. In particular, using the cluster gas mass fractions to break the degeneracy suggests a higher value of $\sigma_8 = 0.85–1.2$

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