Are we missing baryons in galaxy clusters?

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ABSTRACT

The recent constraints on cosmological parameters obtained from the observations of the WMAP satellite limit the cosmic baryon fraction in a range that is larger than, and marginally consistent with, what is measured in galaxy clusters. This raises the question of whether or not we are considering all the ingredients of the cluster baryonic budget. Carefully weighing the baryons in X-ray-emitting plasma and stars in cluster galaxies, I conclude that the cluster baryonic pie consists of 13 (with a 1σ range of 8–19) per cent of stars, 70 (56–89) per cent of intracluster hot medium and 17 (0–33) per cent (and a probability of 73 per cent of being larger than 0) of ‘other’ baryons, presumably in the form of warm (105–107 K) material.

Key words: galaxies: clusters: general – galaxies: fundamental parameters – intergalactic medium – cosmology: observations – dark matter – X-rays: galaxies.

1 INTRODUCTION

The recent analysis of the angular power spectrum of the cosmic microwave background (CMB) obtained from WMAP (Bennett et al. 2003) has provided constraints on the cosmological parameters (Spergel et al. 2003) that confirm with greater accuracy the current energy density of the Universe to be composed of about 73 per cent of dark energy and 27 per cent of matter, mostly non-baryonic and dark. In particular, the quoted constraint on the baryon density, Ω_b, is 0.0224 ± 0.0009h_0^2, and on the total matter density, Ω_m, is 0.135±0.008h_0^2. Consequently, the cosmic baryon fraction, Ω_b/Ω_m, is equal to 0.166±0.002, and the ratio between baryon and cold dark matter density, Ω_b = Ω_m − Ω_b, is equal to 0.199±0.007. These values are expected to be maintained in regions at high overdensities that collapse to form galaxy clusters.

The cluster baryon budget is composed mainly of X-ray-luminous baryons, M_{gas}, of the intracluster medium (ICM) which become hotter upon falling into the cluster dark matter halo by gravitational collapse. Other contributions come from the baryonic stellar mass in galaxies, M_{gal}, and from other ‘exotic’ sources, like intergalactic stars and the still poorly defined baryonic dark matter. Given the large uncertainties on the relative contribution from baryons which are not accounted for in either M_{gas} or M_{gal}, I qualify these as ‘other baryons’, M_{ob}, as already done in a previous paper (Ettori 2001) in which I discussed the constraints on the cluster baryon budget from BOOMERanG and MAXIMA-I data. The tighter constraints on the cosmological parameters provided from WMAP allow now more firm conclusions.

Therefore one can obtain the following relation between the relative amount of baryons in the Universe and in clusters with total gravitating mass M_{tot}:

\[ \frac{\Omega_b}{\Omega_m} = M_b / M_{tot} = f_{gal} Y BC + f_{gal} + f_{ob} / B, \]

where \( f_{gal} = M_{gas} / M_{tot}, \) \( f_{gal} = M_{gal} / M_{tot} \) (≈0.010±0.005 h_0^2 in Fukugita, Hogan & Peebles 1998), \( f_{ob} = M_{ob} / M_{tot}, \) and \( Y \) is the parameter representing the cosmic depletion of baryons at the virial radius with respect to the global value (≈0.92 ± 0.06 from the hydrodynamical simulations of the Santa Barbara Project: Frenk et al. 1999). I parametrize the uncertainties on the measurements of the total gravitating mass and gas mass through the factors \( B \) and \( C \), respectively. These factors act to increase the total mass estimates (i.e. \( B > 1 \)) if corrections to the hydrostatic equilibrium equation are required for bulk motions of the ICM or non-thermal pressure support, and to lower the true gas mass (i.e. \( C > 1 \)) if clumpiness is present in the ICM which is assumed to be smoothly distributed (e.g. Mathiesen, Evrard & Mohr 1999).

In this Letter, I will analyse equation (1) (i) to assess the consistency between the cosmic and the cluster baryon budgets, and (ii) to put significant constraints on \( f_{ob} \). In a consistent way, I adopt the WMAP results on the Hubble constant, \( H_0, \) of 71±0.04 km s\(^{-1}\) Mpc\(^{-1}\) to rescale all the measured quantities.

2 THE COSMIC BARYON BUDGET FROM WMAP

Fig. 1 shows the allowed 1σ region from the WMAP results on the cosmic baryon budget with respect to the observed gas and baryon fractions for a sample of relaxed galaxy clusters at both low and high redshift. All these values are estimated at an overdensity of 200 with respect to the critical density (i.e. within the cluster region that numerical simulations show to be virialized in an \( \Omega_m \)-independent way; see e.g. Evrard et al. 2002). Using a Bayesian approach (Press 1996), I measure the average gas (baryon) fraction and confirm that...
it is consistent between the two samples: $0.107^{+0.028}_{-0.020}$ ($0.133^{+0.029}_{-0.026}$ and $0.111^{+0.069}_{-0.065}$ $0.133^{+0.069}_{-0.065}$) (the error-weighted means of the gas fraction distribution are $0.116 \pm 0.005$ and $0.111 \pm 0.010$ in the low- and high-z samples, respectively. Note that these values do not include any correction by the baryonic depletion which is expected to raise the gas/baryon fraction by about 8/6 per cent at this overdensity. See also Fig. 1 and the text that follows). These estimates are consistent with other, independent, recent determinations (e.g. Allen, Schmidt & Fabian 2001; Pratt & Arnaud 2002) and consistently lower than the baryon budget required from WMAP results. It is worth noting that only the highest estimates of the gas (baryon) mass fraction (e.g. A426, A2142, RX J1350) are perfectly consistent with WMAP results, whereas the other clusters are systematically below them.

To investigate the systematics that could affect this estimate, I change the values of the factors $B$ and $C$ and study their influence on the baryon fraction. The factor $B$, which parametrizes the uncertainties on $M_{\text{tot}}$, is expected to be between 1 and 1.15 from the cluster mass profiles recovered from both X-ray and lensing data (e.g. Allen et al. 2001). The factor $C$ represents the level of clumpiness that affects the estimate of $M_{\text{gas}}$ in X-ray analysis, and which simulations show to be lower than 1.2 (Mathiesen et al. 1999).

Fig. 2 shows that higher values of $B$ and $C$ require a more relevant role to be played by $f_{\text{ab}}$, giving a 2$\sigma$ positive detection for typical values of $Y$ when $B$ and $C$ are 15 per cent larger than the null hypothesis of reliable estimates of both $M_{\text{gas}}$ and $M_{\text{tot}}$ from X-ray analysis.

Moreover, I can estimate from the observables the ratio $R_{\text{gas}} = (\Omega_b/\Omega_m - f_{\text{gal}}/B)/f_{\text{gas}} \times (YBC) \approx (f_{\text{ab}}/f_{\text{gas}} + 1)$ and evaluate the probability that $R_{\text{gas}} > 1$ and a non-zero value of $f_{\text{ab}}$ is required from the data (see Fig. 3). I obtain values of $R_{\text{gas}}$ between 1.3 ($B = 1, C = 1$) and 1.7 ($B = 1.15, C = 1.15$), with an interval accepted at the 95 per cent confidence level of 0.2–2.7. More significantly, this ratio has to be larger than 1 at the 76.6 ($B = 1, C = 1$) and 92.5 ($B = 1.15, C = 1.15$) per cent confidence level. This result gives a high confidence to the conclusion that a significant amount of baryons has to be present apart from what is observed at both X-ray and optical wavelengths.

3 CONCLUSIONS

By comparing the recent cosmological constraints from measurements of the angular power spectrum of the temperature anisotropy in the CMB, carried out with WMAP, with the observed distribution of the gas mass fraction in clusters of galaxies, I draw the following conclusions.

(i) Galaxy clusters with the highest observed gas/baryon fraction are well in agreement with the WMAP estimate of the cosmic baryon budget. On average, however, a disagreement of the order of 15–20 per cent is present, the observed cluster baryon fraction being a lower estimate than the cosmic one. This implies that estimates of the cold dark matter density, $\Omega_c$, made by applying mean results from a large sample of objects, tend to overestimate it. In this perspective, a more ‘realistic’ result is provided from the highest estimate in the distribution of the cluster gas (baryon) mass fraction.

(ii) This dark baryonic component appears to be between a fraction of and up to 2 times the measured gas fraction. Values of $R_{\text{gas}} = (f_{\text{WMAP}} - f_{\text{gal}})/f_{\text{gas}}$ larger than 1 are required from the data with a level of confidence of about 80 per cent and more, if we are underestimating (overestimating) the total (gas) mass. The most probable values are $f_{\text{ab}}/f_{\text{gas}} = R_{\text{gas}} - 1 = 0.3$ ($B = C = 1$) and 0.7 ($B = C = 1.15$), and lower than 1.7 at the 95 per cent confidence level.

It is very unlikely that Galactic objects, such as ‘coloured’ (red, brown, white, beige) dwarfs, stellar remnants and other species of MACHOs (see the review in Gilmore 1999; Evans 2003), or intergalactic ones formed from tidal disruption of cluster dwarfs, like planetary nebulae (e.g. Ciardullo et al. 2002), red giant branch
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Figure 2. Constraints as a function of the depletion parameter $Y$ on the gas (dashed line), stellar (dotted line) and ‘other baryons’ (solid line and probability contours at the $1\sigma$, $2\sigma$ and $3\sigma$ confidence levels) mass fractions normalized to the cosmic value. The shaded region indicates the range of $Y$ permitted from hydrodynamical simulations (Frenk et al. 1999).

Figure 3. Bayesian distribution (Press 1996) of the ratio $R_{\text{gas}} = (f_{\text{WMAP}} - f_{\text{gal}})/f_{\text{gas}}$ for $B = C = 1$ (left) and $B = C = 1.15$ (right).

Stars (e.g. Ferguson, Tanvir & von Hippel 1998) and supernovae (Gal-Yam et al. 2003), can be responsible for such an amount of baryons. It is reasonable to believe that they can contribute by about 0.2 times $f_{\text{gal}}$, or 0.04 $f_{\text{gas}}$.

The most plausible suspect to give so large a contribution is then a X-ray-warm ($10^5 < T < 10^7$ K) intracluster medium (W-ICM). Large-scale cosmological and hydrodynamical simulations by Cen & Ostriker (1999) and Davé et al. (2001) show that the mass fraction at redshift 0 is largely dominated by a warm medium, with a relative contribution in mass that is about a factor of 2 larger than the amount of hot ($T > 10^7$ K) baryons. However, less than 30 per cent of it falls in overdensities $\geq 60$ which are typical of bound structures in a $\Lambda$CDM universe. Furthermore, Bonamente et al. (2002) present evidence of excess in the soft X-ray emission between 0.2 and 0.4 keV in 50 per cent of the 38 clusters in their sample of ROSAT Position Sensitive Proportional Counter observations. They list several suggestions of how to explain this excess, originally observed in the extreme-ultraviolet (Lieu et al. 1996), as both thermal and non-thermal components. If we assign this emission to the baryons that are lacking in our budget, we interpret it as thermal emission due either to the diffuse/halo component of unresolved X-ray-faint cluster galaxies or to the W-ICM. In the first case, we are forced to consider an inexplicably large number of X-ray-emitting member galaxies. More plausible is then the hypothesis of the W-ICM, even though its cooling time tends to be very short with the bulk of the radiation in emission lines if this gas is not primordial. Fabian (1997) suggested that it can be located in turbulent mixing layers lying between embedded cold clouds and the ICM. However, the traditional picture of the efficiency of cooling processes in the cluster cores is no longer supported after XMM and Chandra observations did not report evidence of gas cooler than 1–2 keV (e.g. Peterson et al. 2003) and showed a strong interplay between the ICM, the central active galaxy (e.g. Fabian et al. 2002) and merging cool clumps (e.g. Markevitch et al. 2000; Mazzotta, Edge & Markevitch 2003). On the other hand, the production of thermal energy per particle due to supernovae related to the star formation activity is of the order of $0.4(\eta/0.1)(N_{\text{SNII}}/10^3)(10^{15} M_\odot/M_{\text{gas}})$ keV for a given efficiency $\eta$ in converting the kinetic energy of the explosion into thermal energy through galactic winds, and adopting typical values of the cluster gas mass and number of Type II supernovae as required from the...
observed ICM metallicity. While this energy per gas particle is not enough to stop cooling the hot ICM, it can easily accommodate the survival of the warm component.

Intriguingly, the stronger soft excess detected in ROSAT data from Bonamente et al. (2002) is measured in objects like A85 and A1795, which are the ones lacking most of the baryons with respect to the cosmic budget as plotted in Fig. 1. Significant detections are also present in A2029, A2199 and A3571, whereas a marginal detection is associated with A2142. Nevalainen et al. (2003; see also Kaasra et al. 2003) confirm with XMM the excess in the soft X-ray emission in A1795, and that this excess is best fitted by a thermal component with a characteristic temperature of 0.8 keV, which is about an order of magnitude higher than what is required from ROSAT data but still consistent with our energetic arguments. Using their estimation of the atomic density of the W-ICM in the core of A1795, and assuming that it is broadly distributed like the ICM, one can infer \( f_{\text{W-ICM}}/f_{\text{gas}} = R_{\text{gas}} \approx 0.43 \). In general, values of \( f_{\text{W-ICM}}/f_{\text{gas}} \) between 0.1 and 0.5 are expected.

To summarize, clusters seem to have similar behaviours in accumulating the same relative amount of baryons. It is then their peculiar thermal history, due to the interplay of merging actions and/or activity of the central active galaxy, that provides the baryonic ingredients and cooks the baryonic pie that we taste and show in Fig. 4. To prepare it, I have considered only the eight nearby clusters which provide a more reliable estimate of \( f_{\text{gal}} \) and are less affected by systematics in the determination of \( f_{\text{gas}} \) (see discussion in Ettori, Tozzi & Rosati 2003). I have also corrected the gas fraction by the depletion factor \( Y \approx 0.92 \). The baryonic pie is then made of 70 per cent of hot ICM, with a 1σ range between 56 and 89 per cent and a distribution of the calculated \( f_{\text{gas}}/f_{\text{WMAP}} \) that spans between 28 and 143 per cent at the 2σ confidence level (a higher upper limit is observed in A426 which has a most probable \( f_{\text{gas}}/f_{\text{WMAP}} \) value of 115 per cent). The cold, stellar component is responsible for 13 (1σ: 8–19) per cent, with an observed distribution in the sample between 2 and 37 per cent (2σ lower and upper limits, with the latter reached in A2199, which has a central value of 21 per cent). Finally, a third ingredient, probably a warm ICM, contributes about 17 (0–33) per cent (and a probability of being larger than 0 of 73 per cent) with a distribution that goes from –29 ± 15 per cent in A426 to 40 ± 12 per cent in A1795, one of the objects with the largest detected soft excess (Bonamente et al. 2002; Kaastra et al. 2003).

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**REFERENCES**

Allen S. W., Schmidt R. W., Fabian A. C., 2001, MNRAS, 328, L37
Bennett C. et al., 2003, ApJ, in press (astro-ph/0302208)
Bonamente M., Lieu R., Joy M. K., Nevalainen J. H., 2002, ApJ, 576, 688
Cen R., Ostriker J., 1999, ApJ, 514, 1
Ciardullo R., Feldmeier J. J., Krelove K., Jacoby G. H., Gronwall C., 2002, ApJ, 566, 784
Dave R. et al., 2001, ApJ, 552, 473
Ettori S., 2001, MNRAS, 323, L1
Ettori S., De Grandi S., Molendi S., 2002, A&A, 391, 841
Ettori S., Tozzi P., Rosati P., 2003, A&A, 398, 879
Evans N. W., 2003, in Spooner N., Kudryavtsev V., eds, Proc. 4th Int. Workshop on the Identification of Dark Matter, World Scientific, Singapore, in press (astro-ph/0211302)
Evrard A. E. et al., 2002, ApJ, 573, 7
Fabian A. C., 1997, Sci, 275, 84
Fabian A. C., 2002, in Gilfanov M. et al., eds, Lighthouses of the Universe. Springer-Verlag, Berlin, p. 24
Ferguson H. C., Tanvir N. R., von Hippel T., 1999, Nat, 391, 461
Frenk C. et al., 1999, ApJ, 525, 554
Fukugita M., Hogan C. J., Peebles P. J. E., 1998, ApJ, 503, 518
Gall-Yam A., Maoz D., Guhathakurta P., Filippenko A. V., 2003, AJ, 125, 1087
Gilmore G., 1999, in Spooner N., Kudryavtsev V., eds, Proc. 2nd Int. Workshop on the Identification of Dark Matter. World Scientific, Singapore, p. 121
Girardi M., Manzato P., Mezzetti M., Giuricin G., Limbou F., 2002, ApJ, 569, 720
Kaasra J. S., Lieu R., Tamura T., Paerels F. B. S., den Herder J. W., 2003, A&A, 397, 445
Lieu R., Mittaz J. P. D., Bowyer S., Breen J. O., Lockman F. J., Murphy E. M., Hwang C.-Y., 1996, Sci, 274, 1335
Lin Y. T., Mohr J. J., Stanford S. A., 2003, ApJ, in press (astro-ph/0304033)
Markevitch M. et al., 2000, ApJ, 541, 542
Mathiesen B., Evrard A. E., Mohr J. J., 1999, ApJ, 520, L21
Mazzotta P., Edge A., Markevitch M., 2003, ApJ, submitted (astro-ph/0303144)
Nevalainen J. H., Lieu R., Bonamente M., Lumb D., 2003, ApJ, 584, 716
Peterson J. R., Khan S. M., Paerels F. B. S., Kaastra J. S., Tamura T., Bleeker J. A. M., Ferrigno C., Jernigan J. G., 2003, ApJ, 299, 588
Pratt G. W., Arnaud M., 2002, A&A, 394, 375
Press W. H., 1996, in Ostriker J. P., ed., Unsolved Problems in Astrophysics, Proc. Conf. in Honor of John Bahcall. Princeton Univ. Press, Princeton, NJ (astro-ph/9604126)
Spergel D. M. et al., 2003, ApJ, in press (astro-ph/0302209)

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