Effects of quasar feedback in galaxy groups

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ABSTRACT
We study the effect of quasar feedback on distributions of baryons in galaxy groups using high-resolution numerical simulations. We use the entropy-conserving GADGET code that includes gas cooling and star formation, modified to include a physically based model of quasar feedback. For a sample of 10 galaxy group-sized dark matter haloes with masses in the range of $1–5 \times 10^{13} M_{\odot} h^{-1}$, star formation is suppressed by more than 50 per cent in the inner regions due to the additional pressure support by quasar feedback, while gas is driven from the inner region towards the outer region of the haloes. As a result, the average gas density is 50 per cent lower in the inner region and 10 per cent higher in the outer region in the simulation, compared to a similar simulation with no quasar feedback. Gas pressure is also higher in the outer region, while temperature and entropy are enhanced in the inner region. The total group gas fraction in the two simulations generally differs by less than 10 per cent. We also find a small change of the total thermal Sunyaev–Zeldovich distortion, leading to 10 per cent changes in the microwave angular power spectrum at angular scales below 2 arcmin.

Key words: hydrodynamics – methods: numerical – quasars: general – cosmology: theory.

1 INTRODUCTION
Galaxy clusters and groups are the largest gravitationally bound objects in the universe, and they dominate the total baryon content of the universe. Their spatial distribution and mass function contain information about the formation and evolution of large-scale structure, which in turn constrain a variety of fundamental cosmological properties including normalization of the matter power spectrum, the cosmic baryon density, and dark matter properties. However, in order to use them as a cosmological probe, it is necessary to understand their astrophysical properties, and in particular their baryon physics. This issue is of particular current interest due to upcoming arcminute-resolution microwave sky surveys like ACT (Kosowsky 2006; Fowler et al. 2007) and SPT (Ruhl et al. 2004), which will image galaxy clusters via the Sunyaev–Zeldovich (SZ) distortions to the cosmic microwave blackbody spectrum from the hot electrons in the cluster gas (Sunyaev & Zeldovich 1980).

The majority of baryons in clusters and groups are in the form of hot intracluster gas rather than individual galaxies. Properties of the intracluster medium (ICM) have been studied through a combination of X-ray and radio observations (Fabian et al. 2000; Heinz et al. 2002; Nulsen et al. 2005). Although the dark matter distribution in galaxy clusters follow a self-similar relation (Pointecouteau, Arnaud & Pratt 2005; Vikhlinin et al. 2006), the hot gas does not (Sanderson et al. 2003; Popesso et al. 2005). Additional non-gravitational sources of heating are required to explain the observations. One interesting and plausible possibility is the energy radiated from quasars or active galactic nuclei (AGN) and deposited into the ICM (Kaiser 1991; Valageas & Silk 1999; Nath & Roychowdhury 2002; Scannapieco, Silk & Bouwens 2005; Thacker, Scannapieco & Couchman 2006), which we study in this paper.

The best arena in which to study the impact of various feedback mechanisms is galaxy groups. Massive clusters with deeper gravitational potential wells are likely to have their global thermodynamic and morphological properties less affected by feedback. In comparison, galaxy groups have shallower potential wells while still having enough gas to display the effect of feedback on the ICM. Galaxy groups have recently been observed in X-rays at redshifts as large as $z = 0.6$ (Willis et al. 2005). In the optical band, Tago et al. (2008) have compiled group catalogues from the Sloan Digital Sky Survey (SDSS) Data Release 5 catalogue. Evidence for heating by a central AGN or radio source in galaxy groups and clusters has been the subject of several recent papers (Croston, Hardcastle & Birkinshaw 2005; Sanderson, Finoguenov & Mohr 2005; Jetha et al. 2007). These observations show excess entropy in cluster cores, which suggests that some heating process must act to offset cooling.

In recent years, cosmological simulations including dark matter and gas have been able to follow the evolution of individual
galaxy groups and clusters. A number of studies have investigated the cluster baryon fraction and its evolution in numerical simulations. Adiabatic simulations that do not include radiative cooling find cluster baryon fractions around 0.85 of the universal baryon fraction (Evrard 1990; Metzlter & Evrard 1994; Navarro, Frenk & White 1995; Lubin et al. 1996; Eke, Navarro & Frenk 1998; Frenk et al. 1999; Mohr, Mathiesen & Evrard 1999; Bialek, Evrard & Mohr 2001). Pre-heating the gas reduces the fraction further (Bialek et al. 2001; Borgani et al. 2002; Muanwong et al. 2002; Kay, Thomas & Theuns 2003). When cooling, star formation and other feedback processes are included, the baryon fraction is higher than that obtained from adiabatic simulations (Muanwong et al. 2002; Kay et al. 2003; Valdarnini 2003; Ettori et al. 2004; Nagai, Kravtsov & Vikhlinin 2007). This leads to an ‘overcooling’ problem and indicates an additional feedback mechanism.

In the present paper, we analyse the effect of quasar feedback on the baryon distribution and thermodynamics of hot gas in galaxy groups. We also study its implication for the SZ angular power spectrum, which receives a dominant contribution from high-redshift haloes. Komatsu & Seljak (2002) showed that the thermal SZ angular power spectrum provides a strong constraint on the normalization of the matter power spectrum, $\sigma_8$. Upcoming SZ surveys like ACT or SPT will have sufficient sensitivity to determine $\sigma_8$ with an accuracy limited by uncertainty in the theoretical model. Also, the kinematic SZ effect is a measure of bulk motions in the universe and may be a competitive probe for studying cosmology (Sehgal, Kosowsky & Holder 2005; DeDeo, Spergel & Trac 2005; Bhattacharya & Kosowsky 2007; Hernandez-Monteagudo et al. 2006; Maturi et al. 2007; Roncarelli et al. 2007). But one of the major sources of uncertainty in modelling the kSZ effect is the gas fraction and its evolution. So understanding both the thermal and kinematic SZ signals requires detailed understanding of feedback mechanisms in galaxy clusters and groups. The mechanisms and effects of feedback are also a long-standing question in astrophysics, with particular bearing on the process of galaxy formation.

To this end, we have analysed a sample of 10 galaxy groups at $z = 1$ from numerical cosmological simulations of gas and dark matter which have been extended to include a self-consistent model for the evolution of massive black holes and their baryon feedback. At redshift $z > 1$, the quasar mode of black hole accretion is expected to be the dominant feedback mechanism, compared to the radio-loud accretion mode which becomes important at lower redshifts (Sijacki et al. 2007). The size of our simulations prevents studying feedback in galaxy clusters, but rather restricts us to less massive galaxy groups. But as already mentioned, galaxy groups with shallow potential wells provide the best place to study non-gravitational heating and its implications for the properties of hot gas. High-redshift galaxy groups are also a major contributor to the thermal SZ power spectrum, which peaks around $z \approx 1$, when galaxy groups are more numerous than massive clusters (Komatsu & Seljak 2002).

This paper is organized as follows. Section 2 describes our simulation and its implementation of quasar feedback. In Section 3 we study the effect of numerical resolution on our results; in Section 4 we describe our results and compare them with a simulation that does not include quasar feedback. Finally, in Section 5 we summarize our results and discuss directions for future work, including motivations and prospects for studying more massive galaxy clusters and more realistic feedback modelling for quasars and AGN.

2 SIMULATION

The cosmological simulations used in this study are described in detail in Di Matteo et al. (2008). They use an LCDM cosmological model with parameters consistent with the Wilkinson Microwave Anisotropy Probe (WMAP) first-year results (Spergel et al. 2003): $\Omega_0 = 0.3, \Omega_\Lambda = 0.7$, primordial power spectral index $n = 1$, Hubble parameter $h = 0.7$ with $H_0 = 100 \, h \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, and matter power spectrum normalization $\sigma_8 = 0.9$. A Gaussian random initial condition for this cosmology is evolved from high redshifts to the current epoch using a modified version of the parallel TreePM-SPH code GADGET2 (Springel 2005), which manifestly conserve entropy and energy. Gas dynamics is implemented with the Lagrangian smoothed particle hydrodynamics (SPH) technique (Monaghan 1992). Radiative cooling and heating processes are computed with a spatially uniform photoionizing ultraviolet background (Katz, Weinberg & Hernquist 1996). For modelling star formation and its associated supernova feedback the code uses a subresolution multiphase model for the interstellar medium developed by Springel & Hernquist (2003a). In this model, a thermal instability is assumed to operate above a critical density threshold $\rho_{\text{sh}}$, producing a two-phase medium consisting of cold clouds embedded in a tenuous gas at pressure equilibrium. Stars form from the cold clouds, and short-lived stars supply an energy of $10^{41}$ erg to the surrounding gas as supernovae. This energy heats the diffuse phase of the ISM and evaporates cold clouds, thereby establishing a self-regulation cycle for star formation. The $\rho_{\text{sh}}$ is determined self-consistently in the model by requiring that the EOS is continuous at the onset of star formation. The cloud evaporation process and the cooling function of the gas then determine the temperatures and the mass fractions of the two hot and cold phases of the ISM, such that the EOS of the model can be directly computed as a function of density. The latter is encapsulating the self-regulated nature of star formation owing to supernovae feedback in a simple model for a multiphase ISM. As in the Springel & Hernquist (2003a) model we have included a model for supernova-driven galactic winds with an initial wind speed of $v \sim 480 \, \text{km} \, \text{s}^{-1}$.

A unique aspect of the simulations is their inclusion of supermassive black holes and the resulting energy feedback from mass accretion (Di Matteo et al. 2008). Black holes are represented as collisionless ‘sink’ particles which grow from a seed black hole through accretion of mass from its immediately surrounding gas or through merger with another black hole. Seed black holes of mass $M = 10^5 \, h^{-1} \, M_\odot$ are placed into the centres of haloes whenever they reach a mass threshold of $10^{10} \, h^{-1} \, M_\odot$. The subsequent gas accretion rate on to the black hole is estimated using the Bondi–Hoyle–Lyttleton parametrization (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944; Bondi 1952). We assume a fixed value $\eta = 0.1$ for the radiative efficiency $\eta \equiv L_\gamma/(M_{\text{BH}} c^2)$, where $L_\gamma$ is the radiated luminosity and $M_{\text{BH}}$ is the mass accretion rate. This efficiency is the mean value of a radiatively efficient accretion disc on to a Schwarzschild black hole (Shakura & Sunyaev 1973). We further assume that a fraction $\epsilon_L$ of $L_\gamma$ couples to the surrounding gas in the form of feedback energy $E_F$ deposited isotropically, i.e. $E_L = \epsilon_L L_\gamma$. A fixed value of $\epsilon_L = 0.05$ is adopted here to fit current data on the normalization of the $M_{\text{BH}} - \sigma$ relation between black hole mass and stellar velocity dispersion (Di Matteo, Springel & Hernquist 2005).

We use three different simulation runs, each of box size 33.75 Mpc $h^{-1}$. The box size is a compromise between the requirements of sufficient spatial resolution to resolve physical processes in high-density regions surrounding black holes and sufficient volume to allow formation of haloes with galaxy group masses. We
study haloes at \( z = 1 \): below this redshift, the fundamental modes in the cosmological box become non-linear and the simulations become unreliable on scales of their largest objects (Di Matteo et al. 2003). We name the runs D4 (with and without black holes) and D6 (with black holes), following the naming scheme adopted in Springel & Hernquist (2003b). Runs D4 and D6 include black hole accretion along with cooling, star formation and supernova feedback, while the run D4 (no black holes) leaves out black holes but includes all other physical processes. We use D4 (no black holes) as a baseline comparison simulation to analyse the effects of quasar feedback on galaxy groups for run D4. We also compare D4 and D6 to understand the issues of resolution and convergence. The numerical parameters of the runs, including particle number and mass resolution, are listed in Table 1.

Table 2 lists the radius and mass of the galaxy groups formed in these simulations (the bulk group properties are essentially the same for all three simulations). Masses are defined as the amount of matter contained within a spherical region of overdensity 200 (\( M_{200m} \)) or 500 (\( M_{500m} \)) times the mean density of the universe at \( z = 1 \) (Di Matteo et al. 2003). Fig. 1 shows gas density and star density for the most massive halo (\( M_{200m} = 4.7 \times 10^{13} h^{-1} M_{\odot} \)) in the simulation. The left-hand panel shows the map for each of the properties when black hole feedback is included while the right-hand panel gives the map with no quasar feedback. Note that the gas density maps are colour coded by temperature – the brightness shows the density and the colour represents the temperature. It is evident that the gas is hotter when the feedback is included compared to when not included. Also the distribution of stars has changed significantly when quasar feedback is included.

3 EFFECTS OF NUMERICAL RESOLUTION

To study the effect of quasar feedback on surrounding gas at kiloparsec scales while simultaneously following the formation and evolution of galaxy groups at megaparsec scales. Given this huge dynamic range, it is worthwhile to check how numerical resolution affects our results. We have run two simulations, namely ‘D4’ and ‘D6’, with the same cosmological parameters, namely ‘D4’ and ‘D6’, with the same cosmological parameters, but with different resolution. Table 2 shows the average differential profile in the simulations.

Table 1. Numerical parameters of cosmological simulations (D4 and D6).

| Run | Box size \((h^{-1}\text{Mpc})^3\) | \(N_p\) | \(m_{DM}\) \((h^{-1} M_{\odot})\) | \(m_{gas}\) \((h^{-1} M_{\odot})\) | \(\epsilon\) \((h^{-1}\text{kpc})\) | \(\zeta_{end}\) |
|-----|-----------------|-------|-----------------|-----------------|----------|--------|
| D4  | 33.75 \(2 \times 216\) | 5.6  | 4.71 \(10^{13}\) | 3.08            |
| D6  | 62.75 \(2 \times 486\) | 5.6  | 4.40 \(10^{13}\) | 3.10            |

Table 2. Properties of galaxy groups in the simulations at \( z = 1 \).

| Groups | \(R_{200m}\) \((h^{-1}\text{Mpc})\) | \(R_{500m}\) \((h^{-1}\text{Mpc})\) | \(M_{200m}\) \((10^{13} M_{\odot} h^{-1})\) | \(M_{500m}\) \((10^{13} M_{\odot} h^{-1})\) |
|--------|-----------------|-----------------|-----------------|-----------------|
| 0      | 0.80            | 0.56            | 4.71 \(10^{13}\) | 3.08            |
| 1      | 0.77            | 0.47            | 4.40 \(10^{13}\) | 3.10            |
| 2      | 0.75            | 0.45            | 2.97 \(10^{13}\) | 1.57            |
| 3      | 0.68            | 0.46            | 2.14 \(10^{13}\) | 1.64            |
| 4      | 0.65            | 0.41            | 1.89 \(10^{13}\) | 1.21            |
| 5      | 0.63            | 0.36            | 1.780 \(10^{13}\) | 0.82            |
| 6      | 0.63            | 0.37            | 1.783 \(10^{13}\) | 0.84            |
| 7      | 0.60            | 0.36            | 1.47 \(10^{13}\) | 0.80            |
| 8      | 0.57            | 0.34            | 1.23 \(10^{13}\) | 0.67            |
| 9      | 0.53            | 0.36            | 1.13 \(10^{13}\) | 0.76            |

4 RESULTS

4.1 Thermodynamics of the intracluster medium

In this section we study the impact of quasar feedback on thermodynamics of the ICM, namely on the three quantities, pressure, temperature and entropy. Fig. 3 gives the average temperature profile with scatter around the mean. In the inner region (\( R < 0.2 R_{200m} \)) of the halo, the temperature is enhanced by about 15–20 per cent and by 5–10 per cent in the region \( 0.2 R_{200m} < R < 0.5 R_{200m} \). This is physically reasonable as quasar feedback is coupling part of its radiated thermal energy to the surrounding ICM. We do not see any change in temperature due to quasar feedback at radii outside the halo core. For comparison we also show the average mean profile from the D6 run.

Note, however, that the temperature profile inside the halo core becomes steeper when the feedback is included, whereas the...
observations at low redshift show a rather flat profile inside the core. This disagreement might be either due to the inability of the feedback mechanism to explain the observed temperature profile and an improved model is needed or that one needs to include other sources of feedback in the simulations. Observations of group-sized haloes at high redshift will be needed in order to understand whether the temperature profile indeed gets steeper at higher redshift or a better feedback mechanism is required to explain the flatness of the temperature profile.

The temperature of the system agrees fairly well with previous studies made using haloes of similar mass (Finoguenov, Reiprich & Boumlhringer 2001; Borgani et al. 2004; Khalatyan et al. 2008). For example a halo of mass $4.7 \times 10^{13} M_\odot$ is expected to have a temperature of around 1 keV at $z = 0$. We find a temperature of 1.5 keV for a similar system at $z = 1$. If a virial scaling relation is assumed this translates to a temperature of about 1 keV at $z = 0$ which is consistent with previous studies.

The corresponding average pressure profile is shown in Fig. 4. We find that the pressure decreases for $R < 0.3$ Mpc $h^{-1}$, beyond which quasar feedback clearly leads to a pressure enhancement of 15–20 per cent out to radius of $R_{200}$r. The entropy profile is shown in Fig. 5. The excess entropy near the core region is 50 per cent larger than the no-feedback case. The observational finding for the entropy profile for small groups (Ponman, Sanderson & Finoguenov 2003) agrees fairly well with the current study when virial scaling is assumed to translate the entropy profile at $z = 1$ in the current study to $z = 0$. The scatter around the mean profile for each of these quantities is large, so we need a larger sample size to confirm these systematic deviations. The entropy and pressure profile indicates that the quasar feedback has driven the gas out from the inner region and redistributed in the outer region. The lower panels of the figures show the fractional difference for each quantity. As shown, in the inner region the difference in the profiles is significant; far in excess of the numerical resolution error. Similar differences can be seen in the outside region where the numerical resolution error is few per cent.

### 4.2 Baryon fraction of the intracluster medium

A particularly important issue for interpreting future SZ measurements is the gas fraction in a given halo. Here we consider the
effect of quasar feedback on both baryonic components, stars and hot gas. The 10 most massive objects formed in the simulation have masses ranging from $1$ to $5 \times 10^{13} \, M_\odot \, h^{-1}$. Each object is binned in spherical shells, and the mass fractions of stars, gas and dark matter within each shell are normalized to the primordial baryon fraction $\Omega_b/\Omega_m$. Fig. 6 shows the average differential (left-hand panels) and cumulative (right-hand panels) distribution of gas and stars. Note that the difference in star formation between the simulations with and without quasar feedback is on an average 20–40 per cent out to radius $R_{200}$. It is evident that quasar feedback substantially suppresses star formation at all radii; the cumulative star distribution is 30 per cent lower when feedback is included. The feedback mechanism provides enough pressure support that a significant amount of gas fails to collapse and form stars. Comparing differential and cumulative profiles, it is evident that most of the star formation is suppressed in the interior region of the halo.

Quasar feedback has an equally significant effect on the gas distribution. As shown in the top panel of Fig. 6, hot gas is being driven out from the internal region of the halo ($R < R_{500}$) towards the outer region. The gas density is lowered by 20–30 per cent in the core; to compensate for this depletion, gas density is 10 per cent higher at $R > 0.3 \, R_{200}$, compared to the no-feedback case. As is evident from the cumulative gas distribution, the feedback is not powerful enough to drive the gas from gravitational well of the halo. Note that there is still a difference in total gas mass of around 4 per cent within a radius of $2 \, R_{200}$, which compensates for the lower star formation in these haloes.

Fig. 7 shows cumulative gas and star fractions as a function of halo mass, measured out to radii $R_{200}$, $R_{500}$ and $R_{2500}$, and also between $R_{500}$ and $R_{2500}$. Tables 3–6 give the fractions for individual haloes at these radii and also the mean and scatter. On average, cumulative star fractions shows a 30 per cent depletion at all radii $< R_{500}$, in simulation with quasar feedback; gas fractions show only mild change at $R_{200}$, and $R_{500}$, although at $R_{2500}$ the gas fraction is about 15 per cent lower with quasar feedback. When halo cores are excluded (i.e. between $R_{500}$ and $R_{2500}$), the gas fraction is enhanced by about 10 per cent in simulation with feedback. This again shows that gas is driven off from the inner region of the haloes to outer region. The gas fraction $< R_{500}$ displays a slight trend with mass in both simulations, although the star fraction shows no such effect.
Fig. 3. The mean differential (left-hand panel) and cumulative (right-hand panel) temperature profiles of gas averaged over seven haloes. For each top panel, solid lines represent the mean and scatter around the mean profile for simulation D4 including quasar feedback, while the dotted lines represent the same quantities for simulation D4 with no quasar feedback. Also shown is the mean profile from the D6 run (blue dashed line). The lower panels show the mean fractional change between the haloes in the two runs. The blue dashed line shows the mean and the scatter in the difference in the profiles between D4 and D6 (resolution effect) while the solid red line shows similar difference between the D4 runs (the effect of including the black holes).

Fig. 4. Same as in Fig. 3, except for pressure.

Fig. 8 shows the cumulative ratio of gas to stars. This quantity plays an important role for determining the cosmic matter density (White et al. 1993; Evrard 1997; Allen, Schmidt & Fabian 2002; Allen et al. 2004; Ettori et al. 2004). Usually it is assumed that this ratio is fixed at any radius with negligible redshift evolution (Ettori et al. 2006). We find that this assumption does not hold for either of the simulations. Without quasar feedback, the gas mass-to-stellar mass ratio changes roughly from 2 to 5, a factor of 2.5, between 0.3 $R_{200m}$ and $R_{200m}$; for the simulation including quasar feedback the corresponding change in the ratio is slightly larger, from 2 to 7.5, a factor of 3.5. The ratio rises more steeply for the simulation with feedback and continues increasing beyond $R_{200m}$.

4.3 Thermal Sunyaev–Zeldovich decrements

The thermal SZ distortion from quasar feedback has been studied previously (see e.g. Scannapieco, Thacker & Couchman 2008; Chatterjee & Kosowsky 2007, and references therein). This effect has a systemic impact on galaxy group-sized haloes. As discussed above, the inaccuracy in the pressure profile due to numerical resolution limitations is of the order of 10 per cent for $R < 0.1 R_{200m}$, so we exclude the halo core region when calculating SZ distortions. This does not substantially affect any of our results since the major contribution to the SZ signal comes from the region outside the halo cores (Komatsu & Seljak 2002). We calculate the mean Compton $y$ distortion, which we denote $Y$, by integrating the gas pressure along the line of sight for each halo out to a radius of $R_{200m}$ and over the projected cross-section of the cluster in comoving coordinates. Fig. 9 shows the $Y$ versus mass for the haloes considered here, both with and without quasar feedback, with the lower panel showing the fractional change in $Y$. The individual halo $Y$ parameters are given in Table 7. On average, the $Y$ parameter changes by 6 per cent (excluding the mergers) due to quasar feedback in these galaxy groups. Note that $Y$ parameter in the run with the feedback...
Figure 5. Same as in Fig. 3, except for entropy.

Figure 6. Same as in Fig. 3, except for gas density (top panels) and star density (bottom panels).
Figure 7. Cumulative gas and star fractions for the 10 most massive groups at \(z = 1\) measured within a radius \(R = R_{200m}\) (top left-hand panel), \(R = R_{500m}\) (top right-hand panel) and \(R = R_{2500m}\) (bottom right-hand panel), and between \(R = R_{500m}\) and \(R = R_{2500m}\) (bottom left-hand panel). For each panel, squares represent the star fraction and triangles the gas fraction. Solid lines correspond to the simulation including quasar feedback and dotted lines represent the no-feedback case.

shows both increase and decrease compared to the no-feedback run as a function of mass.

We also give a power-law fit to the \(Y\)–mass relation of the form 

\[
Y/E(z)^{3/5} = 10^\alpha (M_{200m}/10^{14} M_\odot)^\beta
\]

(Sehgal et al. 2007), where \(\alpha\) and \(\beta\) are fitting parameters and \(E(z) = [\Omega_m (1 + z)^{3} + \Omega_\Lambda]^{0.5}\) is the redshift evolution of the Hubble parameter. Although the scatter is large, the power-law fits in both simulations (given in Table 8 are close, and the values are consistent with other studies with larger numbers of haloes (Sehgal et al. 2007).

As shown in Komatsu & Seljak (2002), the SZ power spectrum receives a dominant contribution from high-redshift haloes; especially for \(l > 3000\), the contribution to \(C_l\) comes mostly from \(z > 1\). The halo mass range considered here provides significant contribution to the \(C_l\) for \(l > 5000\) and non-negligible contribution for \(l = 3000–5000\). Since \(C_l \propto Y^2\), we expect that quasar feedback will lead to a systematic increase in \(C_l\) of the order of 10 per cent between \(l = 5000\) and 10 000.

Note that the difference in \(Y\) between the feedback and no-feedback cases does not tend to decrease with mass (Fig. 9), although the scatter is too large to claim any statistical significance of this behaviour. It is imperative to simulate bigger volumes to quantify the effect of quasar feedback on the \(Y\)–mass relation for galaxy clusters, and the corresponding systematic differences in cluster mass estimates. We also emphasize that effect of quasar feedback generally increases with redshift, so our results at \(z = 1\) give conservative estimates of the quasar feedback impact on the SZ signal at earlier times.

5 DISCUSSION

We have studied the effect of quasar feedback on baryon fractions and on thermodynamics of ICM of intermediate-mass haloes corresponding to galaxy groups. Our analysis uses high-resolution \(N\)-body plus hydro cosmological simulations in a box with side length 33.75 Mpc \(h^{-1}\). One simulation is conventional, while another incorporates black hole growth, accretion and energy ejection assuming simple astrophysics consistent with observations; both simulations use the same initial conditions so individual large haloes can be compared. From the 10 most massive haloes, with masses ranging
between 1 and $5 \times 10^{13}$ M$_\odot$ h$^{-1}$, we draw the following conclusions.

(1) Compared to the no-feedback case, star formation is suppressed by 30–40 per cent in the inner regions of the haloes because of the additional pressure support provided by quasar feedback.

(2) Quasar feedback redistributes hot gas, driving it from the inner region towards the outer part of the haloes. As a result, gas density is 20 per cent less in the inner part and 10–15 per cent greater in the outer region when compared to the simulation without feedback. However, the gas fraction in the two simulations differs by only 5–10 per cent, and gas fractions tend to increase mildly with increasing halo mass.

(3) The ratio of gas mass to stellar mass increases by a factor of 3.5 in the simulation including quasar feedback and a factor of 2.5 in the simulation without quasar feedback in the region $0.2 R_{200} < R < 0.5 R_{200}$. This contradicts the common assumption that this ratio is constant at all radii.

(4) Both temperature and entropy increase by 30–50 per cent in the halo core region because of the additional thermal energy radiated by quasars.

(5) Pressure decreases by 30 per cent in the inner region and increases by 15–20 per cent at radii larger than $0.4 R_{200}$ due to the

Figure 8. The average cumulative fraction of the ratio of gas mass and stellar mass for 10 haloes. Solid lines represent the mean and scatter for the sample including quasar feedback, while dotted lines represent the same for the no-feedback case.
We find little dependence of the SZ enhancement with halo mass. The effects of quasar feedback on the ICM will be most evident in the group-sized haloes considered here, with their relatively shallow gravitational potential wells. Observationally, the most interesting haloes, galaxy clusters, are larger in mass by a factor of 10. These are the haloes which are most readily detected via their SZ, X-ray or optical signals. The gas fractions do not show any particular trend with increasing halo mass, and star fractions increase very weakly with mass over the halo mass range studied here. So it is reasonable to expect that the results of this paper will hold for cluster-sized haloes as well. Nevertheless, given the substantial impact of quasar feedback on various properties of the ICM which the current study suggests, it is imperative to study cluster-sized haloes as well. This requires larger volume simulations, as the number density of clusters decreases with cluster mass. To this end, we are currently running a simulation of box size 50 Mpc \( h^{-1} \); results will be reported elsewhere.

This is the first attempt to study the impact of quasar feedback on the baryon fraction and thermodynamics of the ICM in a cosmological hydrodynamic simulation. Both the gas and star fractions in our simulation are consistent with current observational limits (Allen et al. 2004; Ettori & Fabian 1999). Note that we have studied only quasar feedback at redshifts greater than unity. However, AGN also inject energy into the ICM via a ‘radio mode’ which is believed to be the dominant feedback mechanism at lower redshift (Sijacki & Springel 2006; Sijacki et al. 2007). Thus our results should be treated as a conservative estimate of the total impact of AGN feedback for galaxy groups at low redshifts.

Gas pressure in cosmological haloes, particularly those with masses ranging from galaxy groups to galaxy clusters, determines the important thermal SZ signal which will soon be measured with high precision. The gas fraction is important for connecting kinematic SZ signals of cluster gas momentum with theoretical predictions about cluster velocity or total momentum. This paper takes the first step towards quantifying the impact of quasars on these quantities, which turns out to be significant but not dominating. Much work remains to be done, both through larger simulations which contain many galaxy-cluster-sized haloes, and in enhancing the realism of the quasar feedback models. We hope the results here plus the exciting observational prospects in the near future will open the door to further advances in this area.

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Table 7. The relation between SZ Y distortion and cluster mass for galaxy groups with and without quasar feedback.

| \( M_{200m} \) \( (10^{13} \, M_\odot \, h^{-1}) \) | \( Y \) (feedback) \( (10^{-7} \, Mpc^2) \) | \( Y \) (no feedback) \( (10^{-7} \, Mpc^2) \) | \( \Delta Y / Y \) (per cent) |
|---|---|---|---|
| 4.7 | 1.91 | 1.88 | 0.02 |
| 4.4 | 1.43 | 2.06 | -0.44 |
| 2.97 | 0.71 | 0.67 | 0.04 |
| 2.14 | 0.54 | 0.48 | 0.12 |
| 1.89 | 0.37 | 0.37 | 0.01 |
| 1.78 | 0.26 | 0.25 | 0.03 |
| 1.78 | 0.18 | 0.24 | -0.33 |
| 1.47 | 0.21 | 0.24 | -0.11 |
| 1.23 | 0.19 | 0.21 | -0.08 |
| 1.13 | 0.18 | 0.16 | 0.11 |

Table 8. Power-law fits to the SZ Y–mass relation for galaxy groups with and without quasar feedback, as displayed in Fig. 9.

| | \( \alpha \) | \( \beta \) |
|---|---|---|
| With feedback | 1.78 ± 0.06 | -5.55 ± 0.17 |
| No feedback | 1.79 ± 0.05 | -5.47 ± 0.13 |

Figure 9. Sunyaev–Zeldovich Y distortion versus halo mass for 10 haloes, for mass and gas within 1 Mpc \( h^{-1} \) of the halo centre. Squares represent values from simulation D4 including quasar feedback; triangles represent values from simulation D4 without feedback. Lines are the best-fitting power law to the Y–mass relation with quasar feedback (solid) and without quasar feedback (dotted). The lower panel shows the fractional change in Y between the two simulations.
