Ram pressure histories of cluster galaxies

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ABSTRACT
Ram pressure stripping can remove significant amounts of gas from galaxies that orbit in clusters and massive groups, and thus has a large impact on the evolution of cluster galaxies. In this paper, we reconstruct the present-day distribution of ram-pressure, and the ram pressure histories of cluster galaxies. To this aim, we combine the Millennium Simulation and an associated semi-analytic model of galaxy evolution with analytic models for the gas distribution in clusters. We find that about one quarter of galaxies in massive clusters are subject to strong ram-pressures that are likely to cause an expedient loss of all gas. Strong ram-pressures occur predominantly in the inner core of the cluster, where both the gas density and the galaxy velocity are higher. Since their accretion onto a massive system, more than 64 per cent of galaxies that reside in a cluster today have experienced strong ram-pressures of $> 10^{-11}$ dyn cm^{-2} which most likely led to a substantial loss of the gas.

Key words:

1   INTRODUCTION

In clusters, galaxies can lose some or all of their gas by ram pressure stripping (RPS) due to their motion through the intracluster medium (ICM). Both analytical estimates and hydrodynamical simulations show that RPS can remove a significant amount of gas from galaxies, and can thus explain observations such as the HI deficiency of cluster disc galaxies (see e.g. Haynes & Giovanelli 1986; Solanes et al. 2001; Cayatte et al. 1994), and the truncated star forming discs in the Virgo cluster (Warmels 1988; Koopmann & Kenney 2004).

RPS only affects the gaseous component of the galaxy so that a distinct feature of ram pressure stripped galaxies is that their gas discs are distorted or truncated while their stellar discs appear undisturbed. An increasing number of observations of ram-pressure stripped galaxies have become available in the last years (see for example Irwin et al. 1987, Veilleux et al. 1999, Kenney et al. 2004, Vollmer et al. 2004, Chung et al. 2007, Sakelliou et al. 2005; Sun et al. 2007).

RPS is commonly cited in early work as a possible explanation for the increased fraction of S0 galaxies in rich clusters relative to the field (Biermann & Tinsley 1975, Butcher & Oemler 1978). This explanation was dismissed in the original paper by Dressler (1980) on the basis of the observation that the relation between different galaxy populations and local density appears to hold independently of the cluster richness. Later studies pointed out that additional mechanisms that lead to a significant redistribution of mass and/or new star formation are required to explain

the entire S0 population of galaxy clusters (see for example Moran et al. 2007 and references therein).

The role of RPS in the chemical enrichment of the ICM has also been discussed. Observational data suggest that the ICM is enriched with metals to approximately one third of the solar value, suggesting that some fraction of the metals must have originated from cluster galaxies and since been removed from them. Processes responsible for the supply of this enriched gas include AGN feedback (see e.g. Roediger et al. 2007 and references therein), galactic winds driven by supernovae explosions, and ram-pressure stripping (White 1991; Mori & Burkert 2000; Schindler et al. 2005; Domainko et al. 2006). It should be noted, however, that although RPS certainly affects the metallicity of the ICM, it may not be the dominant mechanism. Numerical simulations by Domainko et al. (2006) indicate that RPS can account for only about 10 per cent of the ICM metal content within a radius of 1.3 Mpc.

The first analytical estimate of RPS dates back to the paper by Gunn & Gott (1972) who proposed that for galaxies moving face-on through the ICM the success or failure of RPS can be predicted by comparing the ram pressure with the galactic gravitational restoring force per unit area. Later hydrodynamical simulations of RPS (Abadi et al. 1999, Quilis et al. 2000, Schulz & Struck 2001, Marcolini et al. 2003; Acreman et al. 2003, Roediger & Brüggen 2006, Roediger et al. 2006, Roediger & Brüggen 2007) suggest that this analytical estimate fares fairly well as long as the galaxies are not moving close to edge-on. The ICM-ISM interaction is, however, a complex process influenced by many

parameters. Different aspects have been studied by several groups. Roediger & Hensler (2005) and others have shown that the ICM-ISM interaction is a multistage process: The most important phases are the instantaneous stripping, on a time-scale of a few 10 Myr, an intermediate phase, on a time-scale of up to a few 100 Myr, and a continuous stripping phase that, in principle, could continue until all gas is lost from the galaxy.

While numerical simulations and observations indicate that RPS has important consequences on the amount of gas in cluster galaxies, this physical process is usually not included in semi-analytic models of galaxy formation. The effect of ram-pressure stripping has been discussed only in a couple of studies using semi-analytic models (Okamoto & Nagashima 2003; Lanzoni et al. 2005), and is shown to produce only mild variations in galaxy colours and star formation rates. This happens because the stripping of the hot gas from galactic haloes (strangulation) suppresses the star formation so efficiently that the effect of ram-pressure is only marginal. We note that the studies mentioned above include ram-pressure stripping based on the analytical criterion formulated originally in Gunn & Gott (1972). In recent numerical work, Roediger & Brüggen (2007) have shown that this formulation often yields incorrect mass loss rates. Other numerical studies (e.g. Vollmer et al. (2001)) have argued that ram-pressure stripping can also temporarily enhance star formation. An updated modelling of ram-pressure stripping that takes into account these results has not been included yet in semi-analytic models. We plan to address this in future studies.

For a study of the ram pressure distribution, it is necessary to have information on the dynamics of galaxies and on the properties of the ICM. The dynamics of dark matter halos has been studied in a number of papers using numerical simulations (e.g. Benson 2005; Khochfar & Burkert 2005; Diemand et al. 2004). However, we know of no study on the distribution and history of ram pressures experienced by galaxies in clusters. If ram-pressure plays some role in establishing the observed morphological mix in galaxy clusters and/or the observed radial trends, it is important to quantify the distribution and history of ram pressures experienced by galaxies that reside in clusters today. This is the subject of this paper.

2   METHOD

For this study, we rely on the Millenium simulation described in Springel et al. (2005). This largest dark matter simulation to-date follows $N = 2160^3$ particles of mass $8.5 \times 10^8 h^{-1} M_\odot$ within a comoving box of size $500 \, h^{-1}$ Mpc a side. The underlying cosmological model is a ΛCDM model with $\Omega_m = 0.25$, $\Omega_b = 0.045$, $\Omega_\Lambda = 0.75$, $n = 1$, $\sigma_8 = 0.9$ and $h = 0.73$, where the Hubble constant is parametrised as $H_0 = 100 \, h$ km s^{-1}Mpc^{-1}. Given its high resolution and large volume, this simulation allows us to make statistically significant inferences about the ram pressure histories of galaxies in a representative sample of clusters.

During the simulation, 64 snapshots were saved, together with group catalogues and their embedded substructures. As explained in Springel et al. (2005), dark matter haloes are identified using a standard friends-of-friends (FOF) algorithm with a linking length of 0.2 in units of the mean particle separation. Each FOF group is then decomposed into a set of disjoint substructures identified as a locally overdense region in the density field of the background halo. The selfbound part of the FOF group itself will then also appear in the substructure list and represents what we will refer to below as the main halo. This particular subhalo typically contains 90 per cent of the mass of the FOF group. The group catalogues were then used to construct detailed merging history trees of all gravitationally self-bound dark matter structures. These merger trees form the basic input needed by the semi-analytic model used in De Lucia & Blaizot (2007).

We extracted the orbital parameters of the galaxies from the public archive of the Millenium Run data base[1], and we refer to the original paper for details about the physical processes that are part of the model. Our analysis uses only the orbital parameters of model galaxies and therefore does not rely explicitly on the details of the semi-analytic model itself. One important limitation to take into account is that most of the galaxies in massive clusters are "orphan" galaxies, i.e. galaxies that are not associated with dark matter substructures. As explained in De Lucia & Blaizot (2007) and in previous papers related to this model, substructures allow us to trace the motion of the galaxies sitting at their centres only until tidal truncation and stripping disrupt the substructures down to the resolution limit of the simulation (which for the Millennium Simulation is $1.7 \times 10^{10} M_\odot h^{-1}$) (e.g. De Lucia et al. 2004; Kravtsov et al. 2004). After this time, the galaxy is assumed to merge onto the central galaxy of its own halo on a dynamical friction time-scale, and its position and velocity are traced by tracking the position and velocity of the most bound particle of the halo at the last time there was a substructure. Assuming that the position and velocity of the most bound particle at the last time the substructure could be identified serve as correct initial conditions to track the orbit of the galaxy, the ensuing ram pressure will also be correct. Recent studies (Conroy et al. 2007) have argued that a significant fraction of the satellite population from disrupted subhaloes is unbound and goes to the intra-cluster light component. A large fraction of galaxies in massive haloes is represented by orphan galaxies. If, as argued in Conroy et al. (2007), the model we have used in our study leaves behind an excess of orphan galaxies, this would affect some of the results presented in this study. However, the issue regarding orphan galaxies does not seem to be settled. Wang et al. (2006) have shown that orphan galaxies are needed in order to reproduce the observed correlation function on small scales. The existence of intra-cluster light suggests that tidal effects or mergers can unbind some of the stars in the satellite galaxies. Published results, however, offer little indication of appropriate recipes for treating this process within semi-analytic models. Observationally, the total amount of the intra-cluster light is very difficult to estimate and published

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[1] A description of the publicly available catalogues, and a link to the database can be found at the following webpage: http://mpa-garching.mpg.de/millennium/

estimates vary from less than 20% to more than 50% (see e.g. Zibetti et al. 2005; Gonzalez et al. 2005).

As the Millenium run is a dark-matter only simulation, we have to make assumptions about the distribution of the gas in order to compute the ram pressure exerted on the cluster galaxies. A first estimate is to approximate the ICM as isothermal and hydrostatic in a NFW (Navarro et al. 1996) halo whose profile is given by:

$$\rho_{\rm DM}(r) = \frac{\delta_c \rho_{c0}}{(r/r_s)(1 + r/r_s)^2}, \qquad (1)$$

where ρ_{c0} is the critical density of the universe at $z = 0$, and

$$\delta_c(M) \quad \approx \quad 3 \times 10^3 \Omega_0 [1 + z_{\rm f}(M)]^3, \qquad (2)$$

$$r_s(M) \quad = \quad \frac{r_{\rm vir}(M)}{c(M)} = \frac{1}{c(M)} \left(\frac{3M}{4\pi \Delta_c \rho_{c0}} \right)^{1/3}. \qquad (3)$$

In the above expressions, Ω_0 is the density parameter at $z = 0$, $\Delta_c(\Omega_0, \lambda_0)$ is the collapse factor in a spherical nonlinear model, $z_{\rm f}(M)$ is the average formation redshift of objects of mass M, and $c(M)$ the concentration parameter.

For an isothermal spherical gas cloud with temperature $T_{\rm X}$, the density distribution ρ_g in hydrostatic equilibrium satisfies the equation:

$$\frac{kT_{\rm X}}{\mu m_p} \frac{d \ln \rho_g}{dr} = -\frac{GM(r)}{r^2}, \qquad (4)$$

where μ and m_p denote the mean molecular weight (we adopt 0.59 below) and the proton mass. If one neglects the gas and galaxy contributions to the gravitational mass in the right-hand side, then the mass enclosed within a radius r, can be obtained from Eq. (1) and is given by:

$$M(r) = 4\pi \delta_c \rho_{c0} r_s^3 m(r/r_s), \qquad (5)$$

where $m(r/r_s)$ is the function m evaluated at r/r_s and m is given by

$$m(x) = \ln(1 + x) - \frac{x}{1 + x}. \qquad (6)$$

Equation (4) can be integrated analytically to give

$$\rho_{\rm g}(r) \quad = \quad \rho_{\rm g0} \, \exp \left[-\frac{27b}{2} \left(1 - \frac{\ln(1 + r/r_s)}{r/r_s} \right) \right] \qquad (7)$$

$$= \quad \rho_{\rm g0} \, \exp(-27b/2) \, (1 + r/r_s)^{27b/(2r/r_s)}, \qquad (8)$$

with

$$b \equiv \frac{8\pi G \mu m_p \delta_c(M) \rho_{c0} r_s^2}{27 k T_{\rm X}}, \qquad (9)$$

as shown in Makino et al. (1998). The cluster gas temperature $T_{\rm X}$ is expected to be close to the virial temperature $T_{\rm vir}(M)$ of the dark matter halo. In the profile (1), the latter is in fact dependent on the radius r:

$$kT_{\rm vir}(r) = \gamma \frac{G \mu m_p M(r)}{3r}, \qquad (10)$$

where γ is a fudge factor of order unity which should be determined by the efficiency of the shock heating of the gas.

Eke et al. (1998) adopted $\gamma = 1.5$ as their canonical value in the analysis of X-ray cluster number counts, and this is also the value we use here. Substituting (10) into equation (9), one finds that:

$$b(r) = \frac{2}{9\gamma} \frac{r}{r_s} \left[\ln \left(1 + \frac{r}{r_s} \right) - \frac{r}{r + r_s} \right]^{-1}. \qquad (11)$$

For an absolute determination of the gas profile, we also need an estimate of the cluster gas fraction which we chose to be equal to the universal gas mass fraction $f_{\rm gas} = \Omega_b / \Omega_m = 0.022 h^{-2} / 0.3 = 0.14$. There is evidence that in massive structures such as galaxy clusters this gas fraction is fairly constant over time (Allen et al. 2007; LaRoque et al. 2006). The ram-pressures computed in the following scale simply with this gas fraction.

As shown by Navarro et al. (1996), at large radii the density profile of an isothermal gas drops less rapidly than the dark matter (see their Fig. 14). This levelling (which is observed outside a radius $\sim 2 \times R_{\rm vir}$) is not observed in real clusters (Finoguenov et al. 2001). The model by Makino et al. (1998) has been later extended to non-isothermal gas with a polytropic equation of state (e.g. Suto et al. 1998; Ascasibar et al. 2003, Voit et al. 2002).

One alternative approach to reconstruct cluster mass profiles has been suggested by Komatsu & Seljak (2001). They present an analytic method to predict gas density and temperature profiles in dark matter haloes that does not rely on the isothermal approximation. In this model, the gas density profile traces the dark matter density profile in the outer parts of the haloes (an assumption that is also supported by hydrodynamic simulations), and the gas obeys a polytropic equation of state. In the inner regions of galaxy clusters, gas temperature often increases with radius up to $100 - 200$ kpc and then mildly decreases in the outer regions. The additional assumption that the gas temperature has to vary monotonically with density therefore limits this model to regions outside the inner $100 - 200$ kpc. In the model by Komatsu & Seljak (2001), the gas density distribution is given by:

$$\rho_{\rm gas}(r) = \rho_{\rm gas}(0) y_{\rm gas}(r/r_s), \qquad (12)$$

where $\rho_{\rm gas}(0)$ is the gas density at $r = 0$ and

$$y_{\rm gas}^{\gamma-1}(x) = 1 - 3\eta^{-1} \left(\frac{\gamma - 1}{\gamma} \right) \left[\frac{c}{m(c)} \right] [1 - \ln(1 + x)/x], \qquad (13)$$

where again we assume a NFW density profile of concentration c. The effective value for γ is found to depend weakly on the concentration parameter according to the following equation:

$$\gamma = 1.15 + 0.01 \, (c - 6.5), \qquad (14)$$

and the parameter η is given by

$$\eta(0) = 0.00676 \, (c - 6.5)^2 + 0.206 \, (c - 6.5) + 2.48. \qquad (15)$$

Equations (12)-(15) allow a reconstruction of the gas profile,

and, with the velocity information of the galaxy, of the ram pressure.

Both models discussed above, the isothermal and the Komatsu & Seljak (2001) model, rely on the assumption of hydrostatic equilibrium. Numerical simulations (e.g. Ascasibar et al. 2003) show that that this is not a bad approximation unless they have suffered a major merger in their recent past. However, there is some indication that the dynamic ICM can lead to variations in the ram pressure. E.g. it has been suggested that in the Virgo cluster sloshing motions of the intracluster gas lead to changes in the ram pressure (van Gorkom 2007).

3   RESULTS

3.1   Present-day distribution of galactic ram pressures

In this section, we discuss the distribution of ram-pressures of cluster galaxies at the present epoch (i.e. at $z = 0$). For this analysis, we have selected a number of massive haloes from the Millennium data base, and identified all the galaxies from the De Lucia & Blaizot (2007) semi-analytic catalogue that share the same FOF group. For this analysis we have excluded the central galaxy of each FOF group (i.e. the brightest cluster galaxies).

Our sample is composed of 20 clusters with masses close to $M = 10^{15} M_\odot$ (M_{200} between $7.3 \cdot 10^{14} M_\odot$ and $1.2 \cdot 10^{15} M_\odot$) and 174 clusters with masses close to $M = 10^{14} M_\odot$ (M_{200} between $9.7 \cdot 10^{13} M_\odot$ and $1.03 \cdot 10^{14} M_\odot$), yielding a total of 78,178 and 74,294 galaxies, respectively.

Fig. 1 shows the distribution of instantaneous ram pressures exerted on galaxies within clusters of masses $M = 10^{14} M_\odot$ (black histogram) and $M = 10^{15} M_\odot$ (red histogram). For the $M = 10^{14} M_\odot$ clusters, the distribution peaks at $\sim 10^{-13}$ dyn cm^{-2}, while for the $M = 10^{15} M_\odot$ clusters, it peaks at $\sim 10^{-12}$ dyn cm^{-2} (see caption of Fig. 1 for exact values of the median and the mean). The shapes of the distributions for both mass ranges are very similar, with a tail at lower ram pressures and a fairly sharp cutoff at higher ram pressures. The corresponding plot for the model by Komatsu & Seljak (2001) is shown in Fig. 2. The peaks of the two distributions are at similar ram pressure values. However, in the Komatsu & Seljak (2001) model the cut-off at high ram pressures is less sharp, and the distributions appear to be less skewed. This is because in the isothermal model, the density is underestimated at large radii. Thus galaxies at large distances from the centre (which make up the tail of low ram-pressure values that is visible in Fig. 1) suffer a lower ram pressure in the isothermal model compared to the Komatsu model. In both Figs. 1 and 2, the solid histograms show the mean obtained for all the clusters in each mass bin considered, while the error bars indicate the scatter of the distributions.

According to GG72, the mass lost from a galaxy through RPS depends on the gravitational restoring force per unit area. Clearly, other factors, such as inclination, gas content, morphological type, star formation rates, etc. also play a potentially significant, albeit poorly understood, role. The catalogue compiled by De Lucia & Blaizot (2007) contains information that would allow us to estimate the mass
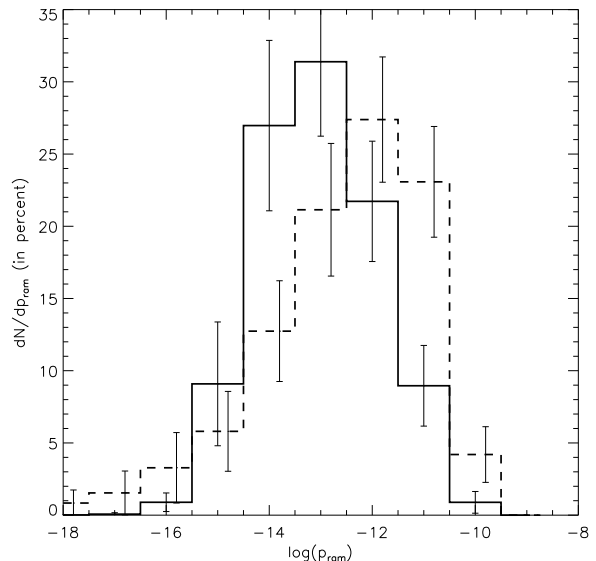

Figure 1. Distribution of galactic ram pressures in isothermal clusters with virial mass $M = 10^{14} M_\odot$ (black) and $M = 10^{15} M_\odot$ (red) at $z = 0$. For $M = 10^{15} M_\odot$, the mean ram pressure is $10^{-10.8}$ dyn cm^{-2} and the median $10^{-11.8}$ dyn cm^{-2}. For $M = 10^{14} M_\odot$, the mean ram pressure is $10^{-11.4}$ dyn cm^{-2} and the median $10^{-12.7}$ dyn cm^{-2}. The error bars denote the cluster-to-cluster scatter.
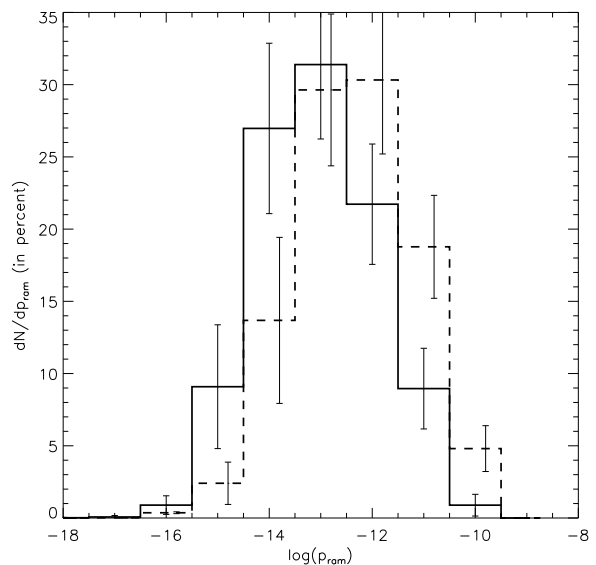

Figure 2. Distribution of galactic ram pressures in clusters with mass $M = 10^{14} M_\odot$ (black) and $M = 10^{15} M_\odot$ (red) at $z = 0$ for the model by Komatsu & Seljak (2001). For $M = 10^{15} M_\odot$, the mean ram pressure is $10^{-10.7}$ dyn cm^{-2} and the median ram pressure is $10^{-11.9}$ dyn cm^{-2}. For $M = 10^{14} M_\odot$, the mean ram pressure is $10^{-11.3}$ dyn cm^{-2} and the median ram pressure is $10^{-12.6}$ dyn cm^{-2}.

loss due to RPS. However, ram-pressure stripping is not self-consistently included in the model. Therefore, we focus here on merely computing the ram-pressures experienced by the galaxies at a given time and position within the cluster.

In the simulations by Roediger & Brüggen (2006), ram pressures of $\sim 10^{-12}$ dyn cm^{-2} were called weak, $\sim 10^{-11}$ dyn cm^{-2} medium and $\sim 10^{-10}$ dyn cm^{-2} strong. Subject to strong ram pressure, a typical spiral galaxy as simulated in Roediger & Brüggen (2006) with mass $\sim 2 \cdot 10^{11} M_\odot$ loses all its gas within ~ 50 Myrs. Medium ram pressure removes approximately half of the gas within ~ 200 Myrs, and weak ram pressure removes relatively little gas. These numbers depend of course on the structure of the gaseous, stellar and dark matter component, and should just serve for orientation. Figs. 1 and 2 show that in a $M = 10^{15} M_\odot$ cluster, approximately 27 per cent of galaxies experience ram pressures of $> 10^{-11}$ dyn cm^{-2} in the isothermal ICM model. In the Komatsu & Seljak (2001) model, the corresponding fraction is about 24 per cent. In a $M = 10^{14} M_\odot$ cluster, these numbers are 10 % for the isothermal model and 9 % for the Komatsu & Seljak (2001) model, respectively.

Since ram-pressure depends on the density of the gas and on the velocity of the galaxy, it is expected to be stronger closer to the centre. In Fig. 3, we plot the ram pressure as a function of radius for the Komatsu (2001) model and a $10^{15} M_\odot$ mass cluster. The distribution shows a sharp upper edge which is determined by the escape velocity at this radius and the gas density at that position. In the isothermal model, the upper envelope can be approximated by:

$$p_{\text{ram}}^{\text{max}}(r) \approx \rho_{\text{g}} \frac{2GM(r)}{r}. \qquad (16)$$

If we approximate $M(r)$ by Eq. (5) and ρ_{g} by Eq. (12), we can rearrange the result to give

$$p_{\text{ram}}^{\text{max}}(x) \approx 8\pi G \rho_{\text{g}0} \delta_c \rho_{c0} r_s^2 \frac{e^{-2B(x)}}{B(x)} (1+x)^{2B(x)/x}, \qquad (17)$$

where $x = r/r_s$ and

$$B(x) = x[\ln(1+x) - x/(1+x)]^{-1}. \qquad (18)$$

Eq. (17) describes the maximum ram pressure pretty well for $x > 0.2$. Similar, though less simple, expressions can be found for the maximum ram pressure in the Komatsu & Seljak (2001) model. For the two gas models, the isothermal and the Komatsu & Seljak (2001) model, the distributions are somewhat different. While within the virial radius the ram pressures are very similar, at larger radii the isothermal model yields lower ram pressures than the Komatsu & Seljak (2001) model. The latter model allows the temperature to decrease at larger radii which leads to a higher density than in the isothermal model. This also explains the narrower distribution of ram pressures shown in Fig. 2 with fewer galaxies in the low ram pressure tail of this distribution.

3.2 Ram pressures histories

In this section, we analyse the ram-pressure history suffered by galaxies that reside in a cluster today. In the following,
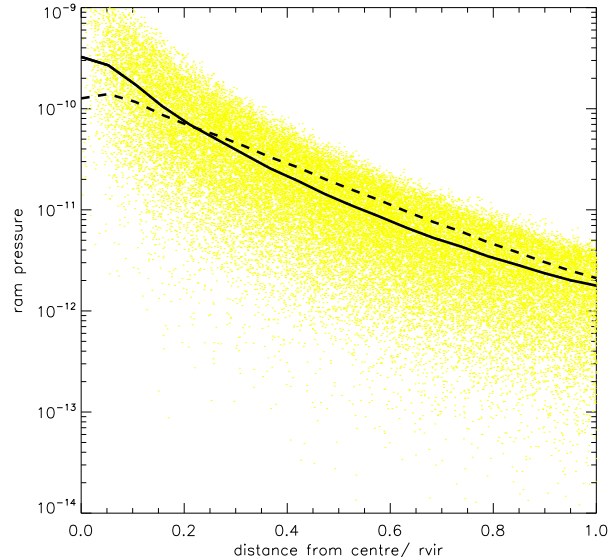

Figure 3. Distribution of galactic ram pressures (in dyn cm^{-2}) with radius in a cluster with mass $M = 10^{15} M_\odot$ at $z = 0$ (model by Komatsu & Seljak 2001). The thick solid line denotes the mean of the distribution. The dashed line shows the mean of the distribution for the isothermal model. The yellow points indicate the ram pressures of the individual galaxies in the Komatsu & Seljak model.

we restrict our analysis to galaxies with with a B-band magnitude mag$_B < -19$, where mag$_B$ is given in the De Lucia & Blaizot (2007) catalogue. For each galaxy, we walk its merger tree backwards in time by linking it with its most massive progenitor at each snapshot until the galaxy becomes a central galaxy of a FOF halo. In Fig. 4, we plot a random selection of the ram pressure histories of galaxies that end up in $M = 10^{15} M_\odot$ clusters. This and the following plots refer to an isothermal ICM (the corresponding results for the Komatsu & Seljak (2001) model are very similar). Fig. 4 shows that the ram pressures fluctuate strongly with time. No strong trend with redshift is visible, showing that galaxies underwent phases of strong ram pressure even at high redshifts. In Fig. 5, we show how the ram pressure (top left panel), the mass of the parent FOF group (top right panel), the relative velocity and the distance to the cluster centre (bottom left panel), and the ambient ICM density (bottom right panel) vary as a function of redshift for a randomly selected galaxy that reside in a $M = 10^{15} M_\odot$ cluster at the present epoch. This plot shows that the galaxy attains high velocities when it passes close to the cluster core. In this region, the ambient ICM density is also highest, such that the highest ram pressures values are obtained. We note that the outputs of the simulation are not sampled finely enough in time to reconstruct the galaxy ram pressure history very accurately. The vertical lines in the top right panel of Fig. 5 show the redshifts of the simulation output. The time between snapshots is too large to sample the orbits of the galaxies with great precision. In some cases, the ram pressure fluctuates by 1-2 orders of magnitudes between snapshots and it is difficult to assess in each case what happens in between. Consequently, the ram pressure histories give conservative bounds on the maximum and minimum
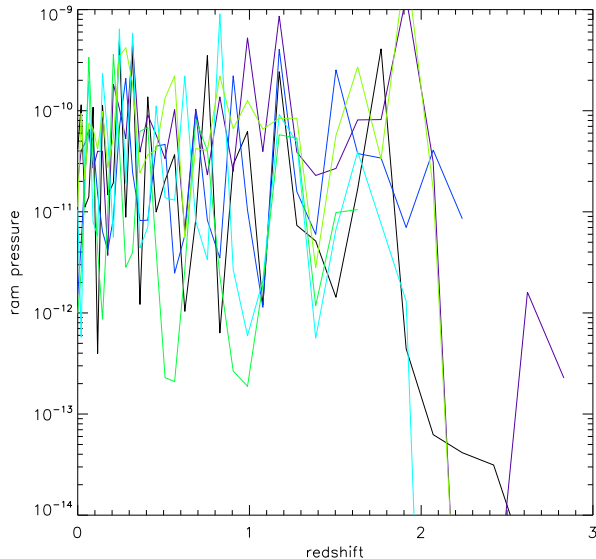
Figure 4. Ram pressure histories of a random sample of galaxies that end up in a $M = 10^{15} M_\odot$ cluster.

ram pressures suffered by each galaxy in the course of its life. We also note that periods of strong ram pressure are often interspersed with periods of weak ram pressure.

In these periods, the interstellar medium could be accreted back onto the galaxy or replenished (by e.g. mergers with gas-rich satellites that have not yet suffered significant stripping). The median redshift at which a galaxy has most recently experienced moderate or strong ram pressure is close to 0.1 for all galaxies in our sample. Strong ram-pressure episodes are, however, expected to have a significant effect on the following evolution of the galaxy. In Fig. 6, we show the maximum ram-pressure that a galaxy (or its most massive progenitor) has experienced since the time of accretion. The solid histogram shows results for a $M = 10^{14} M_\odot$ cluster, while the dashed histogram refers to a $M = 10^{15} M_\odot$ cluster. The figure shows that in a massive cluster, more than 64 per cent of galaxies have experienced ram pressures of $> 10^{-11}$ dyn cm^{-2}, and 32 per cent of galaxies have had ram pressures greater than $> 10^{-10}$ dyn cm^{-2}. Ram pressures of this magnitude most likely strip the galaxy of all its gas in a short time interval of a few million years. The corresponding fraction for a $M = 10^{14} M_\odot$ cluster are lower but still significant (52 per cent and 11 per cent respectively). If ram-pressure stripping is responsible for the morphological transformation of spiral galaxies infalling onto the cluster from the field, these numbers indicate that about half of the galaxies residing today in a $M = 10^{14} M_\odot$ cluster, and a larger fraction for more massive clusters, should be gas poor. Ellipticals and lenticulars make up about $70 - 80$ per cent of the galaxy population of massive clusters in the local Universe (see e.g. Dressler 1980). A significant fraction of these could be therefore entirely explained by ram-pressure stripping.

The original work by Dressler (1980) also showed that there is a clear trend for an increasing fraction of early type galaxies with decreasing distance from the cluster centre. Fig. 7 shows the fraction of galaxies that have suffered
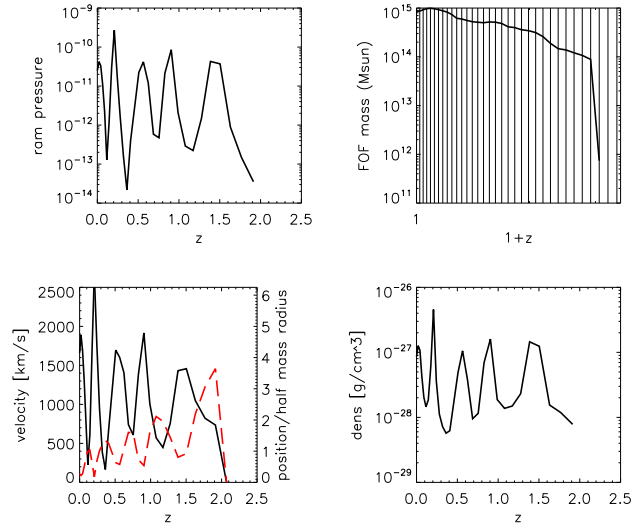

Figure 5. Properties of one selected galaxy versus redshift. Top left: Ram pressure (in dyn cm^{-2}). Top right: Mass of the most massive FOF group (i.e. the host cluster or group) of this galaxy. Vertical lines mark the redshifts of the simulation output. Bottom left: Velocity (black, solid line) and distance to cluster centre (red, dashed). Botton right: Ambient ICM density (using the Komatsu & Seljak (2001) model.
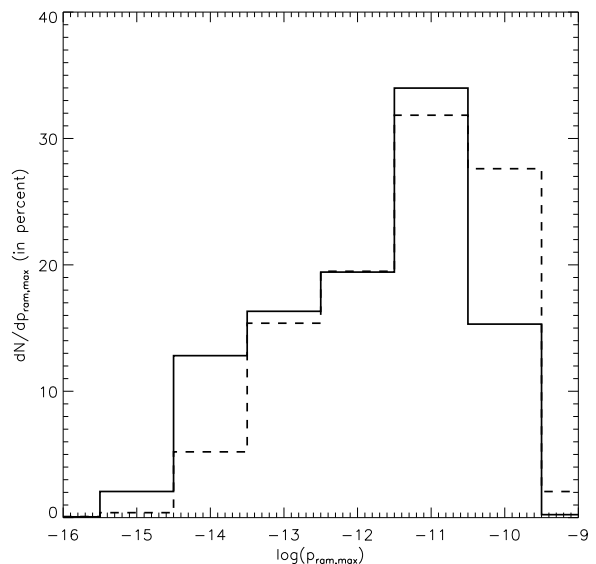

Figure 6. Maximum ram pressure that a galaxy from a $M = 10^{14} M_\odot$ (solid line) and $M = 10^{15} M_\odot$ cluster (dashed line) or its most massive progenitor has experienced during its life time.

strong ($> 10^{-10}$ dyn cm^{-2}), medium ($> 10^{-11}$ dyn cm^{-2}) and weak ($> 10^{-12}$ dyn cm^{-2}) ram pressure as a function of their current ($z = 0$) distance from the cluster centre. The figure clearly shows that a larger fraction of the galaxies that reside in the cluster core have suffered significant ram-pressure. This fraction monotonically decreases with distance from the cluster centre, in qualitative agreement with the observed trends. In $M = 10^{15} M_\odot$ clusters, virtually all galaxies in the inner 300 kpc have suffered strong
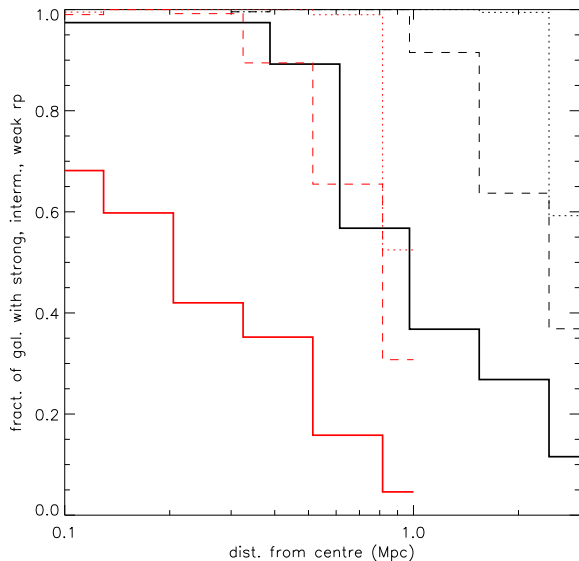
restricted to within the virial radius. Our results show, however, that virtually all the galaxies in clusters suffered weaker episodes of ram pressure, suggesting that this physical process might have a significant role in shaping the observed properties of the entire cluster galaxy population.

The limited number of simulation outputs does not allow us to reconstruct accurately the orbit of the cluster galaxies, and therefore their ram-pressure histories. Our result show that ram pressure fluctuates strongly so that episodes of strong ram-pressure alternate to episode of weaker ram-pressure. During these time intervals, the gaseous reservoir could be replenished and new episodes of star formation could occur. Our results indicate that ram-pressure stripping must play a significant role in the evolution of galaxies residing in massive clusters. A more self-consistent modelling is however required in order to draw more quantitative conclusions about the importance and effects of this physical process.

Figure 7. Fraction of galaxies that have suffered strong (solid line), medium (long-dashed line) and weak (short-dashed line) ram pressure in the course of their history as a function of their current ($z = 0$) position in the cluster. The black lines correspond to $M = 10^{15} M_\odot$ clusters and the red lines to $M = 10^{14} M_\odot$ clusters.

ram pressures after accretion. For $M = 10^{14} M_\odot$ clusters, this fraction decreases to about 2/3. Nearly all galaxies in clusters have experienced medium ram pressures and have thus been influenced to some degree by ram pressure stripping.

4   CONCLUSION

In this study we have taken advantage of the Millennium simulation by Springel et al. (2005) and of the publicly available semi-analytic model by De Lucia & Blaizot (2007) to reconstruct the ram-pressure distribution and ram-pressure history of galaxies that reside in clusters at the present epoch. The gas profile in dark matter is described through two analytic models which give fairly similar results. We have not included ram-pressure stripping self-consistently in the semi-analytic model employed for our study. Instead we have simply used the available information about the orbital distribution and galaxy merging trees to estimate the importance of ram-pressure stripping on galaxies that reside in massive haloes at the present epochs.

We find that more than half of the galaxies in a $M = 10^{15} M_\odot$ cluster, have experienced ram pressures of $> 10^{-11}$ dyn cm^{-2} after their accretion onto a massive system. This fraction is only slightly lower for $M = 10^{14} M_\odot$ clusters, implying that a significant fraction of galaxies in clusters at the present epoch suffered substantial gas loss due to ram pressure stripping. The fraction of galaxies that suffered significant ram-pressure after accretion increases with decreasing distance from the cluster centre, in qualitative agreement with the observed increase of early-type galaxies.

As expected, strong episodes of ram-pressure occur predominantly in the inner core of galaxy clusters, and are

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