The impact of dust on the scaling properties of galaxy clusters

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ABSTRACT
We investigate the effect of dust on the scaling properties of galaxy clusters based on hydrodynamic N-body simulations of structure formation. We have simulated five dust models plus radiative cooling and adiabatic models using the same initial conditions for all runs. The numerical implementation of dust was based on the analytical computations of Montier & Giard. We set up dust simulations to cover different combinations of dust parameters that make evident the effects of size and abundance of dust grains. Comparing our radiative plus dust cooling runs with a purely radiative cooling simulation, we find that dust has an impact on cluster scaling relations. It mainly affects the normalization of the scalings (and their evolution), whereas it introduces no significant differences in their slopes. The strength of the effect critically depends on the dust abundance and grain size parameters as well as on the cluster scaling. Indeed, cooling due to dust is effective in the cluster regime and has a stronger effect on the ‘baryon driven’ statistical properties of clusters such as \(L_X-M\), \(Y-M\), \(S-M\) scaling relations. Major differences, relative to the radiative cooling model, are as high as 25 per cent for the \(L_X-M\) normalization, and about 10 per cent for the \(Y-M\) and \(S-M\) normalizations at redshift zero. On the other hand, we find that dust has almost no impact on the ‘dark matter driven’ \(T_{mw}-M\) scaling relation. The effects are found to be dependent in equal parts on both dust abundances and grain size distributions for the scalings investigated in this paper. Higher dust abundances and smaller grain sizes cause larger departures from the radiative cooling (i.e. with no dust) model.

Key words: methods: numerical – galaxies: clusters: general – large-scale structure of Universe.

1 INTRODUCTION
From the first stages of star and galaxy formation, non-gravitational processes drive together with gravitation the formation and the evolution of structures. The complex physics they involve rule the baryonic component within clusters of galaxies, and in a more general context within the intergalactic medium (IGM; see the review by Voit (2005) and references therein). The study of these processes is the key to our understanding of the formation and evolution of the large-scale structure of the Universe. Indeed, understanding how their heating and cooling abilities affect the thermodynamics of the IGM at large scales and high redshifts, and thus that of the intracluster medium (ICM) once the gas gets accreted on to massive haloes, is a major question still to be answered. The continuous accretion and the merger events through which a halo is assembled lead to a constant interaction of the IGM gas with the evolving galactic component. Within denser environments, like clusters, feedback provided by active galactic nuclei (AGN) balances the gas cooling (see, e.g., Cattaneo & Teyssier 2007; McNamara & Nulsen 2007; Conroy & Ostriker 2008 for a review). Also, from high redshifts, the rate of supernovae drives the strength of the galactic winds and thus the amount of material that ends up being ejected within the IGM and the ICM (see Loewenstein 2006). These ejecta are then mixed in the environment by the action of the surrounding gravitational potential and the dynamics of cluster galaxies within.

For a long time, X-ray observations have shown the abundant presence of heavy elements within the ICM (see e.g., Sarazin 1988; Arnaud 2005). Physical processes like ram-pressure stripping, AGN interaction with the ICM, galaxy–galaxy interaction or mergers are scrutinized within analytical models and numerical simulations in order to explain the presence of metals (see, e.g., Domainko et al. ⋆E-mail: asilva@astro.up.pt

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2 THE DUST MODEL

In our numerical simulations, the implementation of the physical effect of the dust grains is based on the computation by Montier & Giard (2004) of the dust heating/cooling function. In this work, we decided to limit our implementation to the dust cooling effect only. Indeed, the goal of this paper is to study the effect of dust at galaxy cluster scales. The heating by the dust grains is mainly effective at low temperatures (i.e. $T < 10^5$ K) and is a localized effect strongly dependent on the ultraviolet (UV) radiation field. Our numerical simulations (see Sections 3 and 6.2) do not directly implement this level of physics.

The dust grains in a thermal plasma with $10^6 < T < 10^8$ K are destroyed by thermal sputtering, the efficiency of which was quantified by Draine & Salpeter (1979, see their equation 44). The sputtering time depends on the column density and on the grain size. For grain sizes ranging from 0.001 to 0.5 μm, and an optically thin plasma ($n \sim 10^{-3}$ atom cm$^{-3}$), the dust lifetime ranges from $10^8$ yr for small grains up to $10^9$ yr for big grains. These lifetimes are therefore large enough for the cooling by dust in the IGM/ICM to be considered. Evidently, it is also strongly linked to the injection rate of dust, thus to the physical mechanism that can bring and spread dust in the IGM/ICM. In the present work, as a first step, we limit ourselves to a ‘basic’ approach of the implementation of the dust cooling in numerical simulations of structure formation (see Section 2.3). We have not implemented the physical processes of dust creation (i.e. injection in the ICM) and destruction (i.e. sputtering), which de facto put some intrinsic limitations on the derived results (see the discussion in Section 6.2).

Our implementation of the dust cooling power is based on the model of Montier & Giard (2004). We recall below the main aspects of this model and describe the practical implementation within the $N$-body simulations.

2.1 The dust cooling function

Dust grains within a thermal gas such as the ICM or the IGM can be either a heating or a cooling vector depending on the physical state of the surrounding gas and on the radiative environment. Heating can occur via the photoelectric effect if the stellar radiation field (stars and/or QSOs) is strong enough (Weingartner, Draine & Barr 2006 and references therein). Indeed, the binding energies of electrons in the dust grains are small, thus allowing electrons to be more easily photo-detached than in the case of a free atom or a molecule. On the other hand, the cooling by dust occurs through re-radiation in the IR of the collisional energy deposited on grains by impinging free electrons of the ICM/IGM.\footnote{In the galactic medium, the cooling occurs through re-radiation of the power absorbed in the UV and visible range.}

Montier & Giard (2004) have computed the balance of heating and cooling by dust with respect to the dust abundance: cooling by dust dominates at high temperatures in the hot IGM of virialized structures (i.e. clusters of galaxies), and heating by dust dominates in low-temperature plasma under high radiation fluxes such as in the proximity of quasars. The details, of course, depend on the local physical parameters such as the grain size and the gas density.

Assuming local thermal equilibrium for the dust, the overall balance between heating and cooling in the dust grains can be written as follows:

$$\Delta^\delta(a, T_e) = H^\delta_{\text{col}}(a, T_e, n_e).$$ (1)
with \( H_{\text{coll}} \) being the collisional heating function of the grain and \( \Lambda \) the cooling function due to thermal radiation of dust. \( a \) is the grain size, \( T_e \) and \( n_e \) are, respectively, the electronic temperature and density of the medium and \( T_d \) is the dust grain temperature.

The heating of the dust grain was taken from Dwek (1981) and can be expressed in a general way as

\[
H_{\text{coll}}^a(a, T_e, n_e) \propto n_e a^\alpha T_e^\beta,
\]

(2)

where the values of \( \alpha \) and \( \beta \) are dependent on the value of the ratio \( a^{2/3}/T_e \).

The relevant dust parameters affecting the cooling function are the grain size and the metallicity. Indeed, the smaller the grains and the higher the metallicity, the higher is the cooling power of the dust. Thus, the total cooling function due to a population of dust grains can be expressed as a function of these two parameters as

\[
\Lambda(a, T_d) = \int \int \int \Lambda^a(a, T_d) \frac{dn(a, Z, V)}{dV da dZ} dV da dZ,
\]

(3)

where \( \frac{dn(a, Z, V)}{dV da dZ} \) is the differential number of dust grains per size, metallicity and volume element.

Cooling by dust happens to increase with the square root of the gas density, whereas heating by dust is proportional to the density. As stressed by Montier & Giard (2004), cooling by dust is more efficient within the temperature range of \( 10^8 < T < 10^9 \) K (i.e. \( 0.1 < kT < 10 \) keV), which is typically the IGM and ICM thermal condition.

We redirect readers to Montier & Giard (2004) for a full description of the dust model, and a comprehensive physical analysis of the effect of dust in a optically thin plasma.

2.2 The dust abundance

The abundance of dust is a key ingredient to properly weight in our implementation. Observations indicate that dust represents only a tiny fraction of the baryonic matter: \( M_{\text{dust}}/M_{\text{gas}} \approx 0.01 \) in our Milky Way (Dwek, Rephaeli & Mather 1990), and this is possibly lower by a factor of 100–1000 in the ICM: \( M_{\text{dust}}/M_{\text{gas}} = 10^{-3}–10^{-4} \) (Popescu et al. 2000; Aguirre et al. 2001). We defined the abundance of dust as the ratio of the dust mass with respect to the gas mass:

\[
Z_a = \frac{M_{\text{dust}}}{M_{\text{gas}}} = f_a \frac{Z}{Z_{\odot}} Z_{d\odot},
\]

(4)

where \( Z \) is the metallicity in units of solar metallicity, \( Z_{d\odot} = 0.0075 \) is the solar dust abundance, that is the dust-to-gas mass ratio in the solar vicinity (Dwek et al. 1990), and \( f_a \) is the abundance of dust in the ICM in units of solar dust abundance.

Dust enrichment occurs via the feedback of galaxy formation and evolution in the ICM through interaction, stripping, mergers, galactic winds and AGN outbursts. At all redshifts, it is linked to the star formation rate (SFR) which drives the production of dust in cluster galaxies. However, in our hydrodynamic simulations (see Section 3), the SFR is not physically modelled, but it is inferred by the cooling state of the gas particles within the simulations: gas particles below a given threshold of temperature and above a given threshold of density are considered as collisionless matter, forming stars and galaxies (see Section 3). In order to tackle this problem, we choose to directly link the dust abundance to the metal abundance using equation (4). Therefore, the dust distribution in our simulations mimics the metal distribution.

2.3 Implementation in the N-body simulations

From the equations presented in the previous sections, we computed the dust cooling function according to the embedding medium temperature and (global) metallicity. In simulations, once the metallicity and temperature are known, \( a \) and \( f_a \) are the only two parameters driving the dust cooling rate [i.e. \( \Lambda(a, Z) = \Lambda(a, f_a) \)]. In the top panel of Fig. 1, we present dust cooling rates (red lines) for different dust models at the same metallicity \( Z/Z_{\odot} = 0.33 \) (see text). Black, blue and red curves are the total cooling functions, radiative cooling of the gas from Sutherland & Dopita (1993) and dust cooling functions, respectively.

![Figure 1. Cooling functions implemented in the numerical simulations. The top panel shows the dependence of the dust model D1 (\( f_a = 0.1 \) and \( a = 10^{-3} \) \( \mu m \)) on metallicity (and temperature) whereas the bottom panel shows different dust models at the same metallicity \( Z/Z_{\odot} = 0.33 \) (see text). Black, blue and red curves are the total cooling functions, radiative cooling of the gas from Sutherland & Dopita (1993) and dust cooling functions, respectively.](image_url)

(i) We tested three types of sizes: two fixed grain sizes with \( a = 10^{-3} \) and \( 0.5 \) \( \mu m \), respectively, labelled small and big. The third assumes for the IGM dust grains a distribution in sizes as defined by Mathis, Rumpl & Nordsieck (1977) for the galactic dust: \( N(a) \propto a^{-3.5} \) within the size interval of \([0.001, 0.5]\) \( \mu m \). It is hereafter referred to as the ‘MRN’ distribution.

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The amplitude of the K are converted into collisionless baryonic mass on scales of 1–2 Mpc (i.e. an encompassed dust mass $d = 0.9$, $h = 0.7$, boxsize $L = 100 h^{-1} $ Mpc and number of baryonic and dark matter particles, $N = 4 096 000$).

(ii) We investigate three values of $f_d$: 0.001, 0.01 and 0.1. The two extreme values roughly bracket the current theoretical and observational constraints on dust abundance in the ICM/IGM (i.e. $10^{-5}$ and $10^{-3}$ in terms of dust-to-gas mass ratio). Different observations published in the literature give different constraints for this parameter. $Z_d = 5 \times 10^{-3}$ (i.e. $f_d = 0.2$) is the upper limit derived by Giard et al. (2008), while Giard et al. (2008) have statistically detected towards galaxy clusters is produced by thermal emission from intracluster dust. This is very close to the inferred upper limit of $Z_d = 2 \times 10^{-4}$ (i.e. $f_d = 0.08$) that we can derive from the non-detection of the statistical reddening of background galaxies behind 458 RCS clusters of Müller et al. (2008) (the dust mass within the central Mpc is found to be less than $5 \times 10^9 M_\odot$). A very similar work by Boy, Hogg & Moustakas (2008) on Sloan Digital Sky Survey (SDSS) clusters at $z \approx 0.05$ led to a colour excess upper limit of $E(B - V) < 3 \times 10^3$ mag on scales of 1–2 Mpc (i.e. an encompassed dust mass of $10^9 M_\odot$). This value matches the results of Chelouche, Koester & Bowen (2007), who averaged the reddening of QSOs behind the SDSS clusters as a function of the impact parameter on the clusters. These authors measured an average colour excess of $(E(g - i)) \approx 3 \times 10^3$ mag. This detection is statistically significant for large impact parameters, i.e. $1 \leq R \leq 6 - 7 \times R_{200}$ (where $R_{200} \approx 1$ Mpc). If we extrapolate their measurements to the central Mpc of a cluster, this extinction translates into a dust mass of $M_{dust} = 3 \times 10^8 M_\odot$ (see their equation 4). Compared with the corresponding gas mass in the same volume, this leads to $Z_d \approx 10^{-5}$ (i.e. $f_d \approx 0.004$). Our chosen values of $f_d$ thus bracket the range of current observational constraints.

Table 1 lists code names and simulation details of all runs used in this work. In the case of models D1 to D5, simulation cooling rates are given by the added effect of cooling due to dust and radiative gas cooling. Total cooling functions are displayed (non-coloured lines) in the bottom panel of Fig. 1 for each of these models at $Z/Z_\odot = 0.33$. As the figure indicates, the effect of dust cooling is stronger for models with higher dust-to-metal mass abundance parameters, $f_d$, and for smaller grain sizes (model D1). For low values of $f_d$, the impact of dust cooling is significantly reduced. For example, in the case of model D5, the contribution of dust to the total cooling rate is negligible at $Z/Z_\odot = 0.33$ for all temperatures. Therefore, we do not expect to obtain significant differences between simulations with these two models.

Table 1. Simulation parameters: $f_d$, dust-to-metal mass ratios (see equation 4), grain sizes and number of time-steps taken by simulation runs to evolve from $z = 49$ to 0. Cosmological and simulation parameter were set the same in all simulations, as follows: $\Omega = 0.3$, $\Omega_b = 0.7$, $\Omega_b = 0.0486$, $\sigma_b = 0.9$, $h = 0.7$, boxsize $L = 100 h^{-1} $ Mpc and number of baryonic and dark matter particles, $N = 4 096 000$.

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<th>$N_{steps}$</th>
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<td>–</td>
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<tr>
<td>C</td>
<td>Cooling (no dust)</td>
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3 NUMERICAL SIMULATIONS

3.1 Simulation description

Simulations were carried out with the public code package HYDRA, (Couchman, Thomas & Pearce 1995; Pearce & Couchman 1997), an adaptive particle–particle/particle–mesh (AP3M) (Couchman 1991) gravity solver with a formulation of smoothed particle hydrodynamics (SPH), see Thacker & Couchman (2000), that conserves both entropy and energy. In simulations with cooling gas particles are allowed to cool using the method described in Thomas & Couchman (1992) and the cooling rates presented in the previous section. At a given time-step, gas particles with overdensities (relative to the critical density) larger than $10^{15}$ and temperatures below $1.2 \times 10^4 K$ are converted into collisionless baryonic matter and no longer participate in the gas dynamical processes. The gas metallicity is assumed to be a global quantity that evolves with time as $Z = 0.3(t/t_0) Z_\odot$, where $Z_\odot$ is the solar metallicity and $t/t_0$ is the age of the Universe in units of the current time.

All simulations were generated from the same initial conditions snapshot, at $z = 49$. The initial density field was constructed, using $N = 4 096 000$ particles of baryonic and dark matter, perturbed from a regular grid of fixed comoving size $L = 100 h^{-1} $ Mpc. We assumed a cold dark matter cosmology with parameters $\Omega = 0.3$, $\Omega_b = 0.7$, $\Omega_b = 0.0486$, $\sigma_b = 0.9$, $h = 0.7$. The amplitude of the matter power spectrum was normalized with $\sigma_b = 0.9$. The matter power spectrum transfer function was computed using the BBKS formula (Bardeen et al. 1986), with a shape parameter $\Gamma$ given by the formula in Sugiyama (1995). With this choice of parameters, the dark matter and baryon particle masses are $2.1 \times 10^{10}$ and $2.6 \times 10^9 h^{-1} M_\odot$, respectively. The gravitational softening in physical coordinates was $25 h^{-1}$ kpc below $z = 1$ and above this redshift scaled as $50(1+z)^{-1} h^{-1}$ kpc.

We generated a total of seven simulation runs, listed in Table 1. The first two runs, which will be referred to hereafter as ‘adiabatic’ (or model ‘A’) and ‘cooling’ (or model ‘C’) simulations, do not include dust. Simulations 3 to 7 differ only in the dust model parameters assumed in each case, and will be referred to as ‘dust’ runs, and are labelled as ‘D1’ to ‘D5’ models (see Section 2.3 for details on the dust models definition). This will allow us to investigate the effects of the dust model parameters on our results. The last column in the table gives the total number of time-steps required by each simulation to arrive to redshift zero. For each run, we stored a total of 78 snapshots in the redshift range $0 < z < 23.4$. Individual snapshots were dumped at redshift intervals that correspond to the light travel time through the simulation box, i.e. simulation outputs stack in redshift.

3.2 Catalogue construction

Cluster catalogues are generated from simulations using a modified version of the Sussex extraction software developed by Thomas and collaborators (Thomas et al. 1998; Pearce et al. 2000; Muanwong et al. 2001). Briefly, the cluster identification process starts with the creation of a minimal-spanning tree of dark matter particles which is then split into clumps using a maximum linking length equal to $0.5 \Delta_{c}^{1/3}$ times the mean interparticle separation. Here, $\Delta_0$ is the contrast predicted by the spherical collapse model of a virialized sphere (Eke, Navarro & Frenk 1998). A sphere is then grown around the densest dark matter particle in each clump until
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\[ L_X = A_{LM} (M/M_\odot)^{\alpha_{LM}} (1+z)^{\beta_{LM}} E(z)^{y/3}, \]

where \( M_0 = 10^{14} h^{-1} M_\odot \) and the powers of the \( E(z) \) give the predicted evolution, extrapolated from the self-similar model (Kaiser 1986) of the scalings in each case. The quantities \( A, \alpha, \) and \( \beta \) are the scaling normalization at \( z = 0 \), the power on the independent variable, and the departures from the expected self-similar evolution with redshift.

These scalings can be expressed in a condensed form,

\[ y f(z) = \gamma_0(z) (x/x_0)^\delta, \]

where \( y \) and \( x \) are cluster properties (e.g. \( T_{\text{mw}}, M \)) and \( \delta(z) \) is some fixed power of the cosmological factor \( E(z) \). To determine \( A, \alpha, \) and \( \beta \) for each scaling we use the method described in da Silva et al. (2004) and Aghanim, da Silva & Nunes (2009). To summarize, the method involves fitting the simulated cluster populations at each redshift with equations (15) and (16) written in logarithmic form. First, we fit the cluster distributions with a straight line in logarithmic scale at all redshifts. If the logarithmic slope \( \alpha \) remains approximately constant (i.e. shows no systematic variations) within the redshift range of interest, we then set \( \alpha \) as the best-fitting value at \( z = 0 \). Next, we repeat the fitting procedure with \( \alpha \) fixed to \( \alpha(z = 0) \) to determine the scaling normalization factors \( \gamma_0(z) \). This avoids unwanted correlations between \( \alpha \) and \( \gamma_0(z) \).

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\[ \sigma_{\log y'} = \sqrt{\frac{1}{N} \sum_i [\log(y'_i/y_i')]^2}, \]

where \( y' = y f \) (see equation 15) and \( y_i' \) are individual data points. Finally, we perform a linear fit of the normalization factors with redshift in logarithmic scale, see equation (16), to determine the parameters \( A \) and \( \beta \).

We note that above \( z = 1.5 \) the number of clusters in our catalogues decreases typically below 10, hence we do not fit the scaling relations above this redshift value.

5 RESULTS

5.1 Scaling relations at \( z = 0 \)

In this section we present cluster scaling relations obtained from simulations at redshift zero. We investigate the four scalings presented in Section 4 for all models under investigation.

Fig. 2 shows the \( T_{\text{mw}}-M \) (top left panel) \( S_{\text{mw}}-M \) (top right panel), \( Y-M \) (bottom left panel) and \( L_X-M \) (bottom right panel) scalings, with all quantities computed within \( R_{\text{vir}} \). In each case, the main plot shows the cluster distributions for the C (triangles), D4 (diamonds), D2 (filled circles) and D1 (crosses) simulations, whereas the embedded plot presents the power-law best-fitting lines (solid, triple dot-dashed, dashed and dot-dashed for C, D4, D2 and D1 models, respectively) obtained in each case, colour coded in the same way as the cluster distributions. Here, we have chosen to display the dust models that allow us to assess the effect of dust parameters individually. For example, the dust models in runs D4 and D2 only differ by the dust-to-metal mass ratio parameter, whereas models D2 and D1 have different grain sizes but the same \( f_d \). The shaded grey areas in the embedded plots give the rms dispersion of the fit for the cooling (C) model. The dispersions obtained for the other models have similar amplitudes to the C case. The scalings of entropy...
Figure 2. Cluster scalings at redshift zero for $T_{\text{mw}}-M$ (top left panel), $S-M$, (top right panel), $Y-M$ (bottom left panel) and $L_X-M$ (bottom right panel). Displayed quantities are computed within $R_{200}$, the radius where the mean cluster density is 200 times larger than the critical density. Blue colour and triangles stand for the cooling (C) run, cyan and diamonds are for the D4 run, yellow and filled circles are for clusters in the D2 run, and red and crosses are for the D1 run. The lines in the embedded plots are the best-fitting lines to the cluster distributions and the shaded areas are the fit rms dispersions for the C mode, for each scaling.

and X-ray luminosity with mass show larger dispersions because they are more sensitive to the gas physical properties (density and temperature) in the inner parts of clusters than the mass-weighted temperature and $Y$ versus mass relations which are tightly correlated with mass.

An inspection of Fig. 2 allows us to conclude that the cluster scalings laws studied here are sensitive to the underlying dust model, and in particular to models where the dust cooling is stronger (model D1 and D2). The differences are more evident in the $S-M$ and $L_X-M$ scalings, but are also visible, to a lower extent, in the $T_{\text{mw}}-M$ and $Y-M$ relations. Generally, the inclusion of dust tends to increase temperature and entropy because the additional cooling increases the formation of collisionless (star-forming) material, see Fig. 3, leaving the remaining particles in the gas phase with higher mean temperatures and entropies. The decrease of $Y$ and X-ray luminosities reflects the effect of lowering the hot-gas fraction and density due to dust cooling. These effects dominate over the effect of increasing the temperature.

In fact a closer inspection of Fig. 2 indicates that differences for the same cluster in different models (note that all simulations have the same initial conditions so a cluster-to-cluster comparison can be made) reflect the differences of intensity between cooling functions presented in Fig. 1. For example, the differences between models D4 and C are clearly small as one would expect from the small differences between cooling functions displayed in the bottom panel of Fig. 1. Another interesting example is that an increase of one order of magnitude in $f_d$ from D4 to D2 seems to cause a stronger impact in the properties of the most massive clusters than the differences arising from changing the dust grain sizes from D2 to D1. Again this reflects the differences between the cooling functions, which in the latter case are smaller at higher temperatures (see bottom panel of Fig. 1).

A way of quantifying the effect of dust is to look at the best-fitting slope, $\alpha$, and normalization, log $A$, parameters of these scalings which are presented in Table 2 for all cooling models considered in this paper. We find that fitting parameters are quite similar for
models C, D5 and D4 whereas models with high dust abundances provide the strongest variations of the fitting parameters, particularly for the normalizations. In several cases, differences are larger than the (statistical) best-fitting errors, particularly for the D1 and D2 models. We also investigated scalings at redshift zero for the A (adiabatic) model and found they were consistent with self-similar predictions. As expected, the results obtained for the adiabatic and cooling models are in very good agreement with the findings of da Silva et al. (2004) and Aghanim et al. (2009) which use similar simulation parameters and cosmology.

We end this section with a discussion on the amount of condensed baryons (star-forming material) that forms in our simulated cluster populations. Fig. 3 shows the effect of dust on the fraction of condensed baryons (mass of condensed baryons relative to the total mass) for the cluster populations presented in Fig. 2. The additional cooling by dust leads to an additional condensation of gas relative to the cooling model of about 22, 15 and 4 per cent (median values over the displayed range of mass) for the models D1, D2 and D4, respectively. The fraction of baryons that condense out of the ICM in the cooling simulation is about 35 per cent for clusters with $M > 2 \times 10^{14} h^{-1} M_\odot$ and about 45 per cent for systems with lower mass. We note however that our present simulations do not include non-gravitational heating mechanisms to regulate the condensation of gas and therefore overcooling is in practice limited by resolution.

5.2 Evolution of the scaling relations

We now turn to the discussion of the evolution of the cluster scaling laws in our simulations. Here, we apply the fit to a power-law procedure described in Section 4 to derive the logarithmic slope, $\beta$, of our fitting functions, equations (11)–(14). As mentioned earlier, this quantity measures evolution departures relative to the self-similar expectations for each scaling.

In Figs 4–7, we plot the redshift dependence of the power-law slopes, $\alpha$ (top panels), and normalizations, $\log y_0$ (middle panels), for our $T_{\text{mw}}-M$, $S-M$, $Y-M$ and $L_X-M$ scalings, respectively. The bottom panels show straight line best fits, up to $z = 1$, to the data points in the middle panels of each figure. The slopes of these lines are the $\beta$ parameters in equations (11)–(14). We decided not to include data points above $z = 1$ in the computation of $\beta$ because cluster numbers drop rapidly (below 20) which, in some cases, causes large oscillations in the computed normalizations. Moreover in the case of the $L_X-M$ relation, the evolution of $y_0(z)$ with redshift appears to deviate from a straight line above $z \approx 1$. In Table 2, we provide a complete list of the $\log A$, $\beta$ and $\alpha$ fitting parameters and associated statistical errors for all scalings and cooling models investigated in this paper. The displayed values are valid in the redshift range $0 < z < 1$. In the top and middle panels, the coloured bands correspond to the $\pm 1\sigma$ envelope of the best-fitting errors obtained at each redshift for $\alpha$ and $\log y_0$. The shaded areas in the bottom panels are rms fit dispersions of the normalizations, $\log y_0$, computed for the cooling model using equation (17).

Table 2. Best-fitting values of the parameters $\alpha$, $\log A$ and $\beta$ as well as their respective $1\sigma$ errors. These values are valid within the redshift range $0 < z < 1$.

| $T_{\text{mw}}-M$ | $\alpha_{\text{TM}}$ | $\log A_{\text{TM}}$ | $\beta_{\text{TM}}$ | $S-M$ | $\alpha_{\text{SM}}$ | $\log A_{\text{SM}}$ | $\beta_{\text{SM}}$ | $Y-M$ | $\alpha_{\text{YM}}$ | $\log A_{\text{YM}}$ | $\beta_{\text{YM}}$ | $L_X-M$ | $\alpha_{\text{LM}}$ | $\log A_{\text{LM}}$ | $\beta_{\text{LM}}$
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<tbody>
<tr>
<td>Model C</td>
<td>0.61 ± 0.02</td>
<td>0.195 ± 0.002</td>
<td>−0.14 ± 0.01</td>
<td>0.55 ± 0.03</td>
<td>2.443 ± 0.002</td>
<td>−0.33 ± 0.01</td>
<td>1.74 ± 0.03</td>
<td>1.69 ± 0.07</td>
<td>3.330 ± 0.006</td>
<td>0.01 ± 0.03</td>
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<tr>
<td>Model D5</td>
<td>0.61 ± 0.02</td>
<td>0.195 ± 0.003</td>
<td>−0.14 ± 0.01</td>
<td>0.54 ± 0.03</td>
<td>2.444 ± 0.002</td>
<td>−0.34 ± 0.01</td>
<td>1.72 ± 0.03</td>
<td>1.68 ± 0.07</td>
<td>3.334 ± 0.006</td>
<td>−0.02 ± 0.03</td>
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<tr>
<td>Model D4</td>
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<td>0.196 ± 0.002</td>
<td>−0.14 ± 0.01</td>
<td>0.54 ± 0.03</td>
<td>2.445 ± 0.002</td>
<td>−0.34 ± 0.01</td>
<td>1.73 ± 0.03</td>
<td>1.65 ± 0.07</td>
<td>3.333 ± 0.005</td>
<td>−0.02 ± 0.03</td>
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<tr>
<td>Model D2</td>
<td>0.62 ± 0.02</td>
<td>0.197 ± 0.003</td>
<td>−0.15 ± 0.01</td>
<td>0.56 ± 0.03</td>
<td>2.451 ± 0.002</td>
<td>−0.36 ± 0.01</td>
<td>1.72 ± 0.02</td>
<td>1.61 ± 0.08</td>
<td>3.323 ± 0.005</td>
<td>0.02 ± 0.03</td>
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<td>Model D1</td>
<td>0.63 ± 0.02</td>
<td>0.201 ± 0.003</td>
<td>−0.16 ± 0.01</td>
<td>0.55 ± 0.02</td>
<td>2.468 ± 0.002</td>
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<td>1.74 ± 0.02</td>
<td>1.67 ± 0.05</td>
<td>3.265 ± 0.005</td>
<td>0.18 ± 0.03</td>
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<tr>
<td>Model D3</td>
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<td>0.204 ± 0.003</td>
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<td>2.488 ± 0.002</td>
<td>−0.42 ± 0.01</td>
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<td>1.67 ± 0.05</td>
<td>3.207 ± 0.004</td>
<td>0.23 ± 0.03</td>
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Results from different simulation runs are coded in the following way: triangles and solid lines stand for the cooling model, diamonds and triple-dot–dashed lines represent the D4 model, squares and short-dashed lines are for the D3 model, circles and dashed lines are for the D2 models and crosses and dot–dashed lines are for the D1 model. Here, we have omitted the D5 model for clarity. It provides the same fitting results as the cooling model. This confirms expectations and the comments made in the last paragraph of Section 2.3.

The top panels of these figures allow us to conclude that the $\alpha$ slopes of our scalings are fairly insensitive to dust cooling. These also show no evidence of systematic variations with redshift for all scalings, which is an important requirement when fitting the cluster distributions with power laws of the form equations (11)–(14). The redshift independence of the slopes with the dust model confirms our findings at redshift zero. The scatter (non-systematic ‘oscillations’) at high redshift is caused by the decrease of the number of clusters with $M_{\text{lim}} \geq 5 \times 10^{13} \, h^{-1} \, M_\odot$, the sample selection used for all fits.

The main effect of cooling by dust is reflected in the changes it produces in the normalizations of the cluster scaling laws. Again, the impact of dust is different depending on the scaling under consideration. For the $T_{\text{mw}} - M$ scaling in Fig. 4, we see a systematic variation with the dust model (ordered in the following way: C, D4, D3, D2, D1), but differences between models are within the errors and fit dispersions of each other. For the evolution of the normalizations of the $S - M$, $Y - M$ and $L_X - M$ scalings (see Figs 5–7), we conclude that the inclusion of dust cooling causes significant departures from the standard radiative cooling model depending on the dust model parameters. For example, this is clear from the non-overlapping errors and fit dispersions of the normalizations for the D2 and D1 models. For all scalings, the relative strength of the effect of dust follows the relative intensity of the cooling functions presented in Section 2.3. This orders the models in the following way: C, D4, D3, D2, D1 with increasing normalizations for the $T_{\text{mw}} - M$ and $S - M$ scalings and decreasing normalizations for the $Y - M$ and $L_X - M$ relations.

We end this section by noting that we find positive evolution [relative to the expected self-similar evolution, i.e. for a given $x$ in equation (15) the property $y_f$ is higher at higher redshifts] for the $Y - M$ and $L_X - M$ (models D1 and D2 only) relations, whereas the $T_{\text{mw}} - M$ and $S - M$ relations show negative evolution relative to the self-similar model. This is in line with the findings from simulations with radiative cooling of similar size and cosmology (see, e.g., da Silva et al. 2004; Aghanim et al. 2009).

6 DISCUSSION

6.1 Efficiency of the dust cooling

In agreement with the cooling functions of Montier & Giard (2004), the dust cooling is most effective in the cluster temperature regime. The relative importance of the dust cooling with respect to the gas
The impact of dust on cluster scaling laws

(i) The $T_{\text{mw}}-M$ relation is almost unchanged when adding dust cooling to the radiative gas cooling (see Fig. 4). Our results show that the (mass weighted) temperature–mass relation within $R_{200}$ is essentially driven by the gravitational heating of the gas (due to its infall on the cluster potential well), and that the physics of baryons (at least for the physics implemented in the simulations presented in this paper) plays very little role in the outer parts of haloes which dominate the estimation of the mass-weighted temperature and integrated mass. Since gas cooling tends to disturb the dark matter distribution at the centre of clusters in high resolution simulations (Gnedin et al. 2004), the cooling by dust may amplify this effect, and thus modify scaling relations like the $T_{\text{mw}}-M$. In the case of observationally derived quantities, scaling laws will be drawn from overall quantities that will proceed from mixed-projected information over a wide range of radii. If a gradient exists in the dust effect towards the cluster centre, an ‘overall’ temperature might bear the signature of the structural effect of dust. Anyway this quantification is beyond the scope of this paper and will be investigated in a forthcoming paper. There is also no significant effect between the different dust models and the radiative case on the evolution of the slope and normalization of the $T_{\text{mw}}-M$ relation.

(ii) On the other hand, the other three scaling laws are deeply related to the baryonic component of the clusters. The clear effect on the $S-M$, $Y-M$ and $L_X-M$ relations illustrates this fact (see Figs 5–7). We found that the slopes of these scalings remain fairly insensitive to dust, whereas normalizations show significant changes depending on the dust parameters. Relative changes in the normalizations at redshift zero and $M_0 = 10^{14} h^{-1} M_{\odot}$ can be as high as 25 per cent for $L_X-M$ and 10 per cent for the $S-M$, $Y-M$ relations for the D1 model. Models with lower dust abundances and MRN grain size distributions present smaller but systematic variations relative to the C model. As any other cooling process, the cooling due to dust tends to lower the normalizations of the $Y-M$ and $L_X-M$ scalings due to the decrease of the hot gas fractions and densities which dominate the increase of temperature. The increase of normalizations for the $S-M$ and $T_{\text{mw}}-M$ relations with added dust cooling is also in line with expectations because cooling converts cold, dense gas into collisionless star-forming material, which raises the mean temperature and entropy of the remaining gas.

(iii) Our simulations allow us to quantify the relative impact of the dust parameters on the investigated cluster scalings (see Figs 4–7 and Table 2). From one model to another, one can identify two clear effects due to dust. (1) It shows the expected effect of the dust abundance, which from models D4 to D2 increases by a factor of 10, producing a change of normalizations relative to the purely radiative case (model C), from almost 0 per cent contribution to about 14, 5 and 6 per cent contributions for the $L_X-M$, $Y-M$ and $S-M$ relations, respectively. (2) Even more striking is the effect of the intrinsic dust grain physical properties. The variation of normalizations relative to the C model changes from a 0 per cent level for model D4 to about 25 per cent ($L_X-M$) and 10 per cent ($Y-M$ and $S-M$) for model D1 (i.e. the relative change from models D2 to D1 is about 13 and...
5 per cent, respectively). All these percentages were calculated using normalizations at redshift zero and $M_\ast = 10^{11} h^{-1} M_\odot$. Therefore, the size of the grains becomes an equally important parameter varying the efficiency of the dust cooling. The smaller the grain, the stronger the cooling.

(iv) From Figs 4–7 one finds that differences between normalizations become progressively important with decreasing redshift. This confirms expectations because metallicity was modelled in simulations as a linearly increasing function of time. Although our implementation of metallicity should only be regarded as a first order approximation to the modelling of more complex physical processes (acting on scales below the resolution scale of the present set of simulations), it would be interesting to investigate whether a similar effect remains (i.e. the effects of dust become progressively important at low redshift) when such processes are taken into account throughout the formation history of galaxy clusters (see discussion below).

6.2 Limitation of the dust implementation

6.2.1 Injection and destruction of dust in the ICM

In order to implement the presence of dust in the numerical simulations, we chose a ‘zero-order approach’: we directly correlated the presence of dust with the presence of metals under the assumption that there is no segregation in the nature of the material withdrawn from galaxies and injected into the IGM/ICM (metals, gas, stars or dust). However, this assumption suffers from limitations linked to the dust lifetime. Indeed, dust suffers sputtering whereas metals remain (i.e. are not destroyed) in the IGM/ICM. As detailed in Draine & Salpeter (1979) and Montier & Giard (2004), the dust lifetime before sputtering for a thermal plasma (with $10^8 < T < 10^9$ K) can be expressed as

$$\tau_{sput} = 2 \times 10^7 \left( \frac{10^{-3} \text{ cm}^{-3}}{n_H} \right) \left( \frac{a}{0.01 \mu\text{m}} \right) \text{ yr.} \quad (18)$$

Typically, for densities met in the core of dense clusters, i.e. $n_H \sim 10^{-3} \text{ cm}^{-3}$, and grain sizes ranging from 0.001 to 0.5 $\mu$ m, the dust grains have lifetimes of $10^8 < \tau_{dust} < 10^7$ yr. From equation (18), we see that big grains have longer lifetimes than small grains. Although small grains are destroyed quickly, their population is continuously replenished by the sputtering of bigger grains as long as dust keeps being injected into the ICM. The overall efficiency of the cooling by dust in the ICM/IGM is thus strongly linked to the physical processes of dust injection (i.e. enrichment) in the ICM, but also to the medium thermodynamical properties (i.e. temperature and density), the dust grains being destroyed more quickly in denser regions (i.e. the cluster core) where the cooling by dust is also the most efficient. Whether the processes of dust injection replenish the population of the dust grains and balance its destruction by sputtering over large enough time-scales for the dust cooling to be efficient is a question out of reach of our current set of simulations. Indeed, our simulations do not model the physical processes of dust creation and destruction. This will be a further level of development in the implementation of the dust physics in future simulations. Assuming that a full galaxy mass of stars and gas is dispersed to the ICM within $10^7$ yr, and that the dust lifetime in the ICM is of the order of $\tau_{sput} = 10^7$ yr, from equation (4) we can derive a crude estimation for the $f_d$ parameter: $f_d = Z_d^g/Z_d^{gal} = (M_d^{gal}/M_d^{*}) \times (\tau_{gal}/\tau_{sput}) \simeq (1/10) \times (10^7/10^8) \simeq 0.01$. As for the present observational limits, this crude estimate falls within the value of $f_d$ we have tested.

Therefore our whole analysis is to be considered within the framework of our basic implementation of the effects of dust with the objective of assessing whether dust has a significant impact on large-scale structure formation, and consequently to quantify these effects at first order. However, making use of the cooling function by Montier & Giard (2004), we have performed a fully self-consistent implementation of the effect of dust as a cooling vector of the ICM/IGM. Indeed, on the computation of the cooling function, the implementation encapsulates the major physical processes to which dust is subjected and acts as a non-gravitational process at the scale of the ICM and the IGM.

6.2.2 Correlation of the dust and metal abundances

As already mentioned, we directly correlated the abundance of dust with metallicity, thus to the metallicity evolution, the chosen evolution law of which is quite drastic: $Z = 0.3(t/t_0) Z_\odot$. Indeed, if the metallicity at $z = 0$ is normalized to the value of 0.3 $Z_\odot$, it is lowered to ~0.2 at $z = 0.5$ and ~0.1 at $z = 1$. However, other numerical works based on simulations including physical implementation of metal enrichment processes but without dust agree well with observational constraints (mainly provided by X-ray observations of the Fe K line) which indicate high metallicity values, $Z \sim 0.3 Z_\odot$, up to redshifts above 1.0 (Borgani et al. 2008; Cora et al. 2008). This shows that, as for the stellar component which is already in place in galaxies when clusters form, the metal enrichment of the ICM/IGM has occurred through the feedback of galaxy formation and evolution, and therefore it de facto strongly enriched the IGM/ICM below $z = 1$. It also might give hints that the high metallicity of clusters such as the Milky Way is ~0.01 $Z_\odot$. An early enrichment of dust in the IGM and/or the ICM, which once sputtered will provide metals, could explain part of the iron abundances found in the ICM at low redshifts. This hypothesis seems to be consolidated by a few works that have investigated dust as a source for metals in the material stripped from galaxies via dynamical removal within already formed clusters (Aguirre et al. 2001) or via an early IGM enrichment at high redshift during the peak of star formation around $z = 3$ (Bianchi & Ferrara 2005). The latter work stressed that only big grains ($a > 0.1 \mu$m) can be transported on a few $\times 100$ kpc physical scale, however leading to a very inhomogeneous spatial enrichment in metals once the dust grains are sputtered. For all these reasons, by underestimating the metallicity at high redshifts, we might have underestimated the amount of dust injected into the ICM at high redshift, and thus the efficiency of dust cooling when integrated from early epochs down to redshift zero.

7 CONCLUSION

In this work, we have presented the first simulations of structure formation investigating the effect of dust cooling on the properties of the ICM. We have compared simulations with radiative plus dust cooling with respect to a purely radiative cooling simulation. We have shown the following:

(i) The cooling due to dust is effective in the cluster regime and has a significant effect on the baryon driven statistical properties of clusters such as $L_X-M$, $Y-M$, $S-M$ scaling relations. As an added non-gravitational cooling process dust changes the normalization of these laws by a factor up to 25 per cent for the $L_X-M$ relation, and up to 10 per cent for the $Y-M$ and $S-M$ relations. In contrast,
The impact of dust on cluster scaling laws


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