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A phenomenological model for the intracluster medium that matches X-ray and Sunyaev–Zel’dovich observations

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ABSTRACT

Cosmological hydrodynamical simulations of galaxy clusters are still challenged to produce a model for the intracluster medium that matches all aspects of current X-ray and Sunyaev–Zel’dovich observations. To facilitate such comparisons with future simulations and to enable realistic cluster population studies for modelling e.g. non-thermal emission processes, we construct a phenomenological model for the intracluster medium that is based on a representative sample of observed X-ray clusters. We create a mock galaxy cluster catalogue based on the large collisionless N-body simulation MultiDark, by assigning our gas density model to each dark matter cluster halo. Our clusters are classified as cool core and non-cool core according to a dynamical disturbance parameter. We demonstrate that our gas model matches the various observed Sunyaev–Zel’dovich and X-ray scaling relations as well as the X-ray luminosity function, thus enabling to build a reliable mock catalogue for present surveys and forecasts for future experiments. In a companion paper, we apply our catalogues to calculate non-thermal radio and gamma-ray emission of galaxy clusters. We make our cosmologically complete multifrequency mock catalogues for the (non-)thermal cluster emission at different redshifts publicly and freely available online through the MultiDark data base.

Key words: catalogues – galaxies: clusters: intracluster medium – X-rays: galaxies: clusters.

1 INTRODUCTION

Galaxy clusters are the rarest and largest gravitationally collapsed objects in the Universe and form at sites of constructive interference of long waves in the primordial density fluctuations. Clusters reach radial extents of a few Mpc and total masses $M \sim (10^{14} - 10^{15}) M_\odot$, of which galaxies, hot (1–10 keV) gas and dark matter (DM) contribute roughly 5, 15 and 80 per cent, respectively. If the thermal properties of the intracluster medium (ICM) were solely determined by the gravity of the system, then clusters would obey self-similar scaling relations (Kaiser 1986). However, X-ray observations have demonstrated that self-similarity is broken, especially at low-mass scales (see e.g. Voit 2005, for a review). Apparently the energy input from non-gravitational processes associated with galaxy formation have a larger influence in smaller systems, i.e. at scales of galaxy groups.

The central cooling time of the X-ray emitting gas in galaxy clusters and groups is bimodally distributed. Approximately half of all systems have radiative cooling times of less than 1 Gyr and establish a population of cool core clusters (CCCs), while others have cooling times that can be longer than the age of the Universe, forming the non-cool core cluster (NCCC) population (Cavagnolo et al. 2009; Hudson et al. 2010). Several physical processes have been proposed to be responsible for balancing radiative cooling of the low-entropy gas at the centres of CCCs. In particular feedback by active galactic nuclei (AGN) has come into the focus of recent research (McNamara & Nulsen 2007, 2012), owing to the self-regulated nature of the proposed feedback and observational correlations between radio activity and central entropy (which is a proxy for a small cooling time). The underlying physical processes responsible for the heating include dissipation of mechanical heating by outflows, lobes or sound waves from the central AGN (e.g. Churazov et al. 2001; Brüggen & Kaiser 2002; Ruszkowski & Begelman 2002; Gaspari, Brighenti & Temi 2012) or cosmic ray (CR) heating: streaming CRs excite Alfén waves on which they resonantly scatter (Kulsrud & Pearce 1969). Damping of these waves transfers CR energy and momentum to the cooling plasma (Loewenstein, Zweibel & Begelman 1991; Guo & Oh 2008; Enßlin et al. 2011; Wiener, Oh & Guo 2013), heating it at a rate that balances radiative cooling on average at each radius while explaining the observed temperature floor in CCCs by thermal stability of the heating mechanism (Pfrommer 2013).

Modelling the formation and evolution of clusters with cosmological hydrodynamical simulations has been progressively refined over the last years to also include (subresolution models for)
AGN feedback (e.g. Sijacki et al. 2007, 2008; Puchwein, Sijacki & Springel 2008; Dubois et al. 2012; Gaspari et al. 2012; Vazza, Brüggen & Gheller 2013). While the comparison between data and simulations with AGN feedback improved for integrated thermal properties of large cluster samples (Battaglia et al. 2012a,b), there are still notable differences for differential quantities such as the pressure profile (Planck Collaboration et al. 2013a) or the profile of gas mass fractions (Battaglia et al. 2013). These discrepancies (that have been more dramatic in the past without AGN feedback) motivated the development of phenomenological models of the ICM (e.g. Ostriker, Bode & Babul 2005; Capelo, Coppi & Natarajan 2012). Here, we construct a simple and purely phenomenological model that matches all available X-ray and Sunyaev–Zel’dovich (SZ) data with the goal to facilitate comparison with future hydrodynamical simulations, to allow the modelling of non-thermal cluster emission over the entire electromagnetic waveband and finally to enable the construction of cluster mock catalogues of the thermal and non-thermal cluster emission (in the radio, hard X-ray and gamma-ray band) of current and future surveys. Such a model for the ICM needs to be applied to a sample of cluster haloes, which can either be obtained by means of analytical expressions for the cluster mass function (e.g. Jenkins et al. 2001) or cosmological simulations. In this work, we make use of the recent large-volume N-body simulation MultiDark, which employs a flat Λ cold dark matter cosmology (Prada et al. 2012).

Our phenomenological approach uses gas density profiles of a representative sample of observed X-ray clusters, which are complemented by the observed cluster mass-dependent gas mass fractions. The resulting cluster mock sample is then compared to data including the X-ray luminosity function (XLF), the luminosity–mass relation, the X–M relation, and the Y–M relation, where \( Y_X = M_{200} V_{500} T \) with an X-ray-derived mass \( M_{200} \) and temperature \( T \) (Kravtsov, Vikhlinin & Nagai 2006). We additionally compare our \( Y_{SZ} \)–M relation to recent SZ data, where \( Y_{SZ} \) denotes the integrated Compton–y parameter. In a companion paper (Zandanel, Pfommer & Prada 2014, hereafter Paper II), we apply our ICM model to predict the non-thermal radio and gamma-ray emission of a cosmological complete sample of galaxy clusters, enabling valuable insight into the statistics of radio haloes. One of our final data products is a complete cosmological cluster mock catalogue, at different redshifts, containing information of the DM and ICM properties for each object, together with its (non-)thermal emission at different frequencies. All the products can be found on-line at the MultiDark data base (www.multidark.org).

In Section 2, we introduce the MultiDark simulation along with our selected cluster halo sample. We assign to each of our clusters the phenomenologically constructed gas density profile in Section 3. In Sections 4 and 5, we show that this approach can successfully reproduce the observed X-ray and SZ cluster data. We present the resulting mock cluster catalogues in Section 6, and eventually summarize in Section 7. In this work, the cluster mass \( M_A \) and radius \( R_A \) are defined with respect to a density that is \( \Delta = 200 \) or 500 times the critical density of the Universe. We adopt density parameters of \( \Omega_m = 0.27, \Omega_{\Lambda} = 0.73 \) and today’s Hubble constant of \( H_0 = 100 h_{70} \text{km s}^{-1} \text{Mpc}^{-1} \), where \( h_{70} = 0.7 \).

### 3 GAS DENSITY MODELLING

We decided to use a phenomenological approach and construct the gas density profiles directly from X-ray observations. A suitable X-ray sample that provides the required information is the Representative XMM–Newton Cluster Structure Survey (REXCESS) sample (Croston et al. 2008; Pratt et al. 2009). It is a sample of 31 galaxy clusters of different dynamical states at redshifts \( 0.06 < z < 0.18 \) with detailed information on the de-projected electron density profiles (Croston et al. 2008). In Fig. 1, we show the 31 electron density profiles of the REXCESS sample colour coded by NCCCs and CCCs.

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Table 1. Number of haloes in the final cluster sample.

| Redshift \( z \) | Number of haloes |
|------------------|------------------|
| 0.0              | 13 763           |
| 0.1              | 12 398           |
| 0.18             | 11 106           |
| 0.2              | 10 783           |
| 0.4              | 7 789            |
| 0.53             | 6079             |
| 0.61             | 5187             |
| 0.78             | 3372             |
| 1.0              | 1 803            |

*Note.* We show the number of haloes in our MultiDark snapshots at redshift \( z \) for \( M_{200} \geq 1 \times 10^{14} h^{-1} M_{\odot} \approx 1.4 \times 10^{14} h_{70}^{-1} M_{\odot} \). More snapshots can be found online at www.multidark.org.
n = \frac{n_0}{x^\alpha [1 + x^\beta]^{\alpha/\beta}}.

(1)

where \( x = R/R_c \) and \( R_c \) is the cluster core radius. To reduce the dimensionality of our fit, we fix representative values of \( R_c = 0.2 R_{500} \), \( \alpha = 1 \) and \( \delta = 2.5 \). We fit the radial density profiles of the REXCESS sample in log–log space, separating them in the two categories of NCCCs and CCCs as shown in Fig. 1. We obtain \( n_0, \text{NCCC} = 1.02 \times 10^{-2} \text{ cm}^{-3} \), \( n_0, \text{CCC} = 8.32 \times 10^{-3} \text{ cm}^{-3} \), \( \beta, \text{NCCC} = -0.093 \) and \( \beta, \text{CCC} = 0.592 \). The resulting fits are shown in blue and red for the NCCC and CCC population, respectively.

The next step is to introduce a mass scaling in order to apply our GNFW profiles to clusters of all masses. We adopt the gas mass fraction–mass scaling, \( f_{\text{gas,500}} = 0.04 \) (Sun et al. 2009) and (adopt their equation 8). We can express \( f_{\text{gas,500}} \) in the following way:

\[
f_{\text{gas,500}} = \frac{M_{\text{gas,500}}}{M_{500}} = \frac{\int_{0}^{R_{500}} \rho_{\text{gas}} \, dV}{M_{500}}.
\]

with \( \rho_{\text{gas}}(R) = \rho_{\text{gas}} = n_e m_p / (X_H X_e) \), where \( m_p \) is the proton mass, \( X_H = 0.76 \) is the primordial hydrogen mass fraction and \( X_e = 1.157 \) the ratio of electron-to-hydrogen number densities in the fully ionized CDM (Sarazin 1988). For each cluster \( i \) of our sample, we then define a mass-scaled gas profile as \( \rho_{\text{gas},i} = C_i \rho_{\text{gas}} \) with

\[
C_i = \left( \frac{0.0656 \pm (0.0064 g_1)}{h_{70}^{1.5}} \right)^{1/5} \left( \frac{M_{500,i}}{1.04 \times 10^{15} h_{70}^{-1} M_\odot} \right)^{0.135 + (0.030 g_2)} \int_{0}^{R_{500,i}} \rho_{\text{gas}} \, dV.
\]

where \( g_1 \) and \( g_2 \) are random Gaussian numbers, which we use in order to simulate the natural scatter of the gas profiles.\(^1\)

Hence, for each cluster in our sample we obtain a gas density profile \( \rho_{\text{gas},i} \) that obeys the observed \( f_{\text{gas,500}} \) relation and is uniquely determined by its total mass \( M_{500,i} \), and by the property of being a NCCC or CCC. We assign the latter property to every halo depending on its merging history. In particular, we make use of the offset parameter \( X_{\text{off}} \) computed for the MultiDark halo catalogue. This is defined as the distance from the halo centre to the centre of mass in units of the virial radius. This parameter assesses the dynamical state of the cluster and whether the halo has experienced a recent merger or not. Current observations reveal a ratio of NCCCs and CCCs of about 50 per cent (e.g. Chen et al. 2007; Sanderson, O’Sullivan & Ponman 2009). Since there is a correlation between merging clusters and NCCCs, we use the median of the \( X_{\text{off}} \) distribution to separate our sample into CCCs and NCCCs (with NCCCs defined to be those haloes with the larger dynamical offsets). Clearly, this is an oversimplification, and future X-ray surveys will have to determine this property also as a function of redshift.

We also account for redshift evolution of the gas profiles. While our NCCC and CCC gas profiles as derived from the REXCESS cluster sample are merely used to define a profile shape, the normalization of the gas profiles is set by the observational \( f_{\text{gas,500}} = M_{500} \) relation (Sun et al. 2009). The 43 clusters used in Sun et al. (2009) have redshifts 0.012 < \( z \) < 0.12 with a median of \( z \approx 0.04 \). Thus, our phenomenological gas profile is representative of the cluster population at \( z \approx 0 \). To extend this profile to high-\( z \), we adopt a self-similar scaling of the gas density as \( \rho_{\text{gas}}(z) = E(z)^{\beta} \rho_{\text{gas}}(z = 0) \), where \( E(z)^2 = \Omega_m (1 + z)^3 + \Omega_{\Lambda} \).

As a cautionary remark, we emphasize that our model has been constructed to be valid within \( R_{500} \) and more work is needed to extrapolate it to larger cluster radii, particularly for the thermal cluster emission. Those cluster regions are characterized by a steadily increasing level of kinetic-to-thermal pressure support (e.g. Lau, Kravtsov & Nagai 2009; Battaglia et al. 2012a), dust clumping (Nagai & Lau 2011; Battaglia et al. 2013) and asphericity and ellipticity of the halo morphologies (Battaglia et al. 2013), in particular beyond the virial radius where the filamentary cosmic web connects to the cluster interiors.

### 4 X-RAY OBSERVABLES

So far, we used a well-observed representative sample of X-ray clusters (REXCESS) that was supplemented with X-ray data on gas mass fractions to construct our phenomenological gas model. Here, we will test how our cluster mock data compare to various X-ray inferred observables, which are obtained from different cluster samples and from (partially) different X-ray observatories. Those include the observed \( L_{\text{bol}} \) relation, the \( Y_X \) relation and the XLF.

#### 4.1 Scaling relations

First, we calculate the bolometric thermal bremsstrahlung luminosity \( L_{\text{bol}} \) following Sarazin (1988).\(^2\) To assign a temperature to our

\(^2\) We check our procedure by fitting each of the 31 REXCESS clusters with equation (1) and calculate \( L_{\text{bol}} \) using the measured gas temperature of each cluster. As a result, we fall short of the observed luminosity by a mean (median) of about 21 per cent (20 per cent). This is acceptable considering that we do not permit the parameters \( R_c, \alpha \) and \( \delta \) to vary between different objects. Additionally, we neglect atomic line emission which may give a noticeable contribution, in particular for low-mass clusters and in the cluster outskirts of larger systems.
model clusters (that is needed for calculating $L_{\text{bol}}$ and $Y_X$), we adopt the $T$–$M_{500}$ relation by Mantz et al. (2010b):

$$\log_{10}(k_BT_{\text{ci}}) = A + B \log_{10} \left( \frac{E(z)M_{500}}{10^{14.7}h_{70}^{-2}M_{\odot}} \right),$$

where $A = 0.91$, $B = 0.46$ and $T_{\text{ci}}$ is the cluster temperature not centrally excised (Mantz et al. 2010b). Mantz et al. (2010b) report a scatter of $\sigma_{yx} = 0.06$, which we apply to our sample using Gaussian deviates.

In the left-hand panel of Fig. 2, we show how our model $L_{\text{bol}}$–$M_{500}$ relation compares with observations by Mantz et al. (2010b) (all data, see their table 7). Their sample is composed of 238 clusters at $0.02 < z < 0.46$ with a median of $z \approx 0.2$ and self-consistently takes into account all selection effects, covariances, systematic uncertainties and the cluster mass function (Mantz et al. 2010a). For this reason, we compare the Mantz et al. (2010b) data to our model at $z = 0.2$, and limit the comparison to the mass range covered by the observations. Overall, there is reassuring agreement between our phenomenological model and the data, which probe our model most closely on scales around the cluster core radii (which is where the contribution to $L_X$ per logarithmic interval in radius, $dL_X/d \log r \propto r^2n_{\text{gas}}(r)\sqrt{k_BT}$, approximately attains its maximum). In Table 2, we show our model $L_{\text{bol}}$–$M_{500}$ scaling relation and its scatter for different redshifts. We find that the scatter of our samples at all redshifts is Gaussian distributed with a standard deviation of $\sigma_{yx} \approx 0.18$ that matches the observational results of Mantz et al. (2010b), which report a scatter of $\sigma_{yx} = 0.185$.

In the right-hand panel of Fig. 2, we compare the $Y_X$–$M_{500}$ relation of our sample to observational data (Mantz et al. 2010b). The model agrees nicely at the high-mass end, but underpredicts the observed scaling at low masses by about 20 percent (at the 1$\sigma$ level). This is the same level of deviation from the data as in the case of $L_X$, which is more significant due to the smaller scatter in the $Y_X$ relation. The differential contribution to the thermal energy per logarithmic interval in radius (and hence to the integrated Compton-$y$ parameter) is given by $dY/d \log r \propto r^3P_{\text{th}}(r)$, with the thermal gas pressure $P_{\text{th}} = n_{\text{gas}}k_BT$. It peaks at scales slightly smaller than $R_{500}$ with 1$\sigma$ contributions extending out to 3 $R_{500}$ (Battaglia et al. 2010). Hence, the observational scaling constrains our model on those large scales, quite complementary to the X-ray luminosity. The deviations at small masses either indicate tensions with our assumptions on $f_{\text{gas}}$, the gas temperature or different selection effects of either observational sample that we use for model calibration and comparison. Mantz et al. (2010b) determine their masses by adopting a constant value for $f_{\text{gas}}$, in contrast to our approach which adopts the observed $f_{\text{gas}}$–$M_{500}$ relation given by Sun et al. (2009). Additionally, we adopt the Mantz et al. (2010b) centrally included temperature throughout all our work, while Mantz et al. (2010b) use the centrally excised temperature to calculate $Y_X$. This assumption also impacts the scatter of the $Y_X$–$M$ relation. In fact, using the centrally included temperature, we found a scatter of $\sigma_{yx} \approx 0.11$.

Table 2. $L_{\text{bol}}$–$M_{500}$ scaling relations.

| Redshift $z$ | $A$   | $B$   | $\sigma_{yx}$ |
|--------------|-------|-------|---------------|
| 0            | 21.41 | 0.11  | 0.185         |
| 0.1          | 21.30 | 0.12  | 0.179         |
| 0.18         | 21.49 | 0.13  | 0.177         |
| 0.2          | 21.50 | 0.13  | 0.178         |
| 0.4          | 21.13 | 0.17  | 0.178         |
| 0.55         | 21.45 | 0.19  | 0.176         |
| 0.61         | 21.60 | 0.22  | 0.177         |
| 0.78         | 20.73 | 0.29  | 0.177         |
| 1            | 20.45 | 0.42  | 0.177         |

Note. Scaling relations are reported in the form of $\log_{10}(L_{\text{bol}}/E(z)h_{70}^{-2}10^{44}\text{erg s}^{-1}) = A + B \log_{10}(E(z)M_{500}/h_{70}^{-1}M_{\odot})$. The relation scatter $\sigma_{yx}$ is also shown.

3 Scatter is calculated as $\sigma_{yx} = \sqrt{\left\{ \sum_i N_i [Y_i - (A + BX_i)]^2 \right\} / N - 1}$, where the sum extends over the data points $X_i, Y_i$, and $A$ and $B$ are the fit parameters.
4.2 Luminosity functions

Studies of the XLF got out of fashion during the last years due to the difficulties of using the X-ray luminosity for cosmological purposes. The X-ray emissivity scales with the square of the gas density, which makes it subject to density variations and clumping. This implies large scatter that causes a large Malmquist bias and underlines the necessity of careful mock surveys that need to address all systematics.

Nevertheless, it provides a complementary check for our model. To this end, we use the XLF of the ROSAT Brightest Cluster Sample (BCS; Ebeling et al. 1997), which is in good agreement with results from the ROSAT ESO Flux-Limited X-ray (REFLEX; Böhringer et al. 2002) and Highest X-ray Flux Galaxy Cluster Sample (HIFLUGCS; Reiprich & Böhringer 2002). Note that the XLF is fully determined by the mass function and the \( L_X-M_{500} \) relation after taking into account the observational biases. This means that applying the Malmquist and Eddington-bias-corrected \( L_X-M_{500} \) relation by Mantz et al. (2010b) directly to the MultiDark mass function and accounting for the observational scatter in \( L_X-M_{500} \) should yield an unbiased XLF.

We show the resulting bolometric and soft-band (0.1–2.4 keV) XLF in Fig. 3 and compare those to the corresponding BCS XLFs and to our model predictions. Note that there is only the Schechter fit available for the BCS bolometric XLF. While the soft-band XLF by Mantz et al. (2010b) agrees well with the BCS data points, it deviates from the corresponding Schechter fit. We also show the bolometric XLF of Mantz et al. (2010b) and the bolometric XLF of our model at \( z = 0.1 \). The XLFs are calculated in equally log-spaced mass bins; the error bars represent the Poissonian errors. Note that we limit the comparison to the luminosity range covered by our sample. We impose a low-luminosity cut to avoid a drop in the XLF due to the imposed mass cut.

Table 3. \( Y_{X,500-M_{500}} \) scaling relations.

| Redshift \( z \) | \( A \) | \( B \) | \( \sigma_y \) |
|---------|---------|---------|--------|
| 0       | -9.09 ± 0.07 | 1.60 ± 0.01 | 0.109 |
| 0.1     | -8.90 ± 0.07 | 1.59 ± 0.01 | 0.109 |
| 0.18    | -8.90 ± 0.08 | 1.59 ± 0.01 | 0.109 |
| 0.2     | -8.83 ± 0.08 | 1.59 ± 0.01 | 0.109 |
| 0.4     | -8.78 ± 0.10 | 1.59 ± 0.01 | 0.108 |
| 0.53    | -8.62 ± 0.12 | 1.60 ± 0.01 | 0.108 |
| 0.61    | -8.74 ± 0.14 | 1.59 ± 0.01 | 0.108 |
| 0.78    | -8.40 ± 0.18 | 1.58 ± 0.01 | 0.109 |
| 1       | -8.30 ± 0.26 | 1.58 ± 0.02 | 0.109 |

Note. Scaling relations are reported in the form of \( \log_{10}(E(z)f_X/\sigma_{500}/\mathcal{M}_\odot \text{ keV}) = A + B \log_{10}(M_{500}/\mathcal{M}_\odot) \). The relation scatter \( \sigma_y \) is also shown.

Figure 3. Bolometric and soft-band (0.1–2.4 keV) XLFs. Shown are the soft-band data points, the soft-band and bolometric Schechter fits of the BCS sample of Ebeling et al. (1997), which has a median of \( z \approx 0.08 \). While the soft-band XLF deviates from the adopted temperature scaling of our model (following Battaglia et al. 2011) and further studies in this direction are desirable. For these reasons, we do not show XLF predictions at other redshifts, leaving this for a future study.

5 SZ SCALING RELATIONS

In the left-hand panel of Fig. 4, we compare the \( Y_{SZ-M_{500}} \) relation of our model (following Battaglia et al. 2012a, equation 3) with the observed scaling relation by the Planck Collaboration et al. (2013b). We use the Planck COSMO sample, which is Malmquist-bias corrected and has a median redshift of 0.18, and compare this to our \( z = 0.18 \) relation. Our model reproduces the normalization of the scaling relation remarkably well, except for the high-mass end where our simulations have a weaker constraining power due to the smaller box size in comparison to the survey volume of Planck. However, the slope of the MultiDark \( Y_{SZ-M_{500}} \) relation (1.59 ± 0.01) is shallower in comparison to the self-similar slope (5/3) as well as the observed slope of the Planck COSMO sample. We can analytically understand the cluster–mass scaling of our model by considering its mass-dependent quantities, namely \( Y_{SZ} \propto M_{500} f_{\text{gas}} T \propto M_{500}^{1.595} \). In particular, we can trace back the shallower slope to the adopted temperature scaling of our model (\( T \propto M_{500}^{1/3} \)), which includes the cluster core region and yields a shallower mass scaling in comparison to the self-similar expectation (\( T \propto M_{500}^{2/3} \)). The temperature scaling is only partially countered by the scaling of the gas mass fraction with cluster mass, \( f_{\text{gas}} \propto M_{500}^{1.155} \). To improve upon this, we would have to account for a slightly steeper temperature–mass scaling relation (e.g. using a centrally excised temperature scaling; see Mantz et al. 2010b) in the outer cluster parts that are of relevance for the SZ flux, as explained in Section 4.1. We find a scatter of \( \sigma_y \approx 0.11 \) which compares well
with the Planck result of $\sigma_{\Delta} \approx 0.08$. In Table 4, we report our SZ scaling relations for different redshifts.

In the right-hand panel of Fig. 4, we compare our scaling relation to the recent Atacama Cosmology Telescope (ACT) sample (Hasselfield et al. 2013), which has a median redshift of $z = 0.53$. Again, the slope of our modelled scaling relation is slightly shallower in comparison to the observed slope. Most strikingly, there appears to be a 30% offset from the scaling relations, which could be due to a number of reasons. On the data side, these could include possible selection effects of the different cluster samples or possible biases associated with density clumping and/or non-thermal pressure contributions inherited from the X-ray informed post-processing that was employed by the ACT collaboration to construct their $\Delta_{500}$ estimates. This could also indicate that our model is too simplistic to capture the rich cluster physics and potentially may even point to selection effects of the different cluster samples or possible biases associated with density clumping and/or non-thermal pressure contributions inherited from the X-ray informed post-processing that was employed by the ACT collaboration to construct their $\Delta_{500}$ estimates. However, note that our scaling relation at $z = 0.53$ ($A = -27.67 \pm 0.12$, $B = 1.60 \pm 0.01$) is within the uncertainties compatible with that of the ACT sample ($A = -28.57 \pm 2.25$, $B = 1.65 \pm 0.15$). Thus, we conclude that overall there is reasonable agreement between our phenomenological model and the SZ data of the Planck and ACT collaborations.

### Table 4. $Y_{\text{SZ}, 500}$–$M_{500}$ scaling relations.

| Redshift $z$ | $A$  | $B$   | $\sigma_{\Delta}$ |
|--------------|------|-------|------------------|
| 0            | -27.93 ± 0.07 | 1.60 ± 0.01 | 0.109            |
| 0.1          | -27.75 ± 0.07 | 1.59 ± 0.01 | 0.109            |
| 0.18         | -27.75 ± 0.08 | 1.59 ± 0.01 | 0.109            |
| 0.2          | -27.68 ± 0.08 | 1.59 ± 0.01 | 0.109            |
| 0.4          | -27.62 ± 0.10 | 1.59 ± 0.01 | 0.108            |
| 0.53         | -27.67 ± 0.12 | 1.60 ± 0.01 | 0.109            |
| 0.61         | -27.59 ± 0.13 | 1.59 ± 0.01 | 0.109            |
| 0.78         | -27.26 ± 0.26 | 1.58 ± 0.01 | 0.109            |
| 1.0          | -27.17 ± 0.26 | 1.58 ± 0.02 | 0.109            |

Note. Scaling relations are reported in the form of $\log_{10}(E(z)\Delta_{500}/h_{70}^{-2} M_{\odot}) = A + B \log_{10}(M_{500}/h_{70} M_{\odot})$. The relation scatter $\sigma_{\Delta}$ is also shown.

### 6 Multifrequency Mock Catalogues

As a final product of this work, we construct cosmologically complete mock catalogues of galaxy clusters at different redshifts (see Table 1) for $M_{200} \geq 1 \times 10^{14} h^{-1} M_{\odot} \approx 1.4 \times 10^{14} h_{70}^{-1} M_{\odot}$. We make these catalogues publicly available through the MultiDark data base (www.multidark.org) where we will also post possible updates.

Our catalogues contain all the information regarding the DM properties of each cluster as given by the corresponding original MultiDark BDM halo catalogues. Additionally, we include the following information:

(i) $M_{500}$ and $R_{500}$ calculated from $M_{200}$ and $R_{200}$ of the BDM catalogues with the Hu & Kravtsov (2003) method.

(ii) The ICM X-ray temperature assigned via the $T_{X} - M_{500}$ relation by Mantz et al. (2010b).

(iii) A flag identifying the cluster as NCCC or CCC, as described in Section 3.

(iv) The central gas density $\rho_{\text{gas}, 0}$ with which the full ICM radial profile can be calculated as in Section 3.

(v) The bolometric X-ray thermal bremsstrahlung luminosity $L_{X, \text{bol}}$ within $R_{500}$.

(vi) The $T_{X}$ and $Y_{\text{SZ}}$ parameters within $R_{500}$.

In Paper II, we present a model that allows us to compute the possible radio and gamma-ray emission for each cluster in our mock catalogue, as result of the CR proton–proton interactions with the ICM. We refer to that paper for all the details. However, we want to point out that our mock catalogues also include the following.

(i) A flag identifying whether a given object is a radio-loud or a radio-quiet cluster.
(ii) The CR-to-thermal pressure averaged over the cluster volume within $R_{500}$.
(iii) The radio synchrotron luminosity of secondary electrons that are produced in hadronic CR proton–proton interactions, within $R_{500}$, at 120 MHz and 1.4 GHz.
(iv) The gamma-ray luminosity, within $R_{500}$, above 100 MeV and 100 GeV.

We note that our mock catalogues are not appropriate for all purposes because the density profiles that we adopt in our model represent the average cluster population of cool core and non-cool core systems (while we account for scatter in the gas mass fractions, i.e. the normalization of the profiles). As such, our mocks are very useful as a baseline for comparisons to new hydrodynamical simulations and to new observational samples, as well as for non-thermal modelling of clusters. On the contrary, in the current form they are not appropriate to perform detailed cosmology studies. Careful modelling of the response function of the considered instrument, in combination with light-cone mock catalogues, would be required in this case. Nevertheless, for volume-limited cluster samples, our mock catalogues will certainly serve as valuable tools.

7 DISCUSSION AND CONCLUSIONS

We build a complete cosmological sample of galaxy clusters from the MultiDark N-body simulation with redshifts ranging from $z = 0$ to 1 and construct a phenomenological model for the ICM. This is characterized by X-ray-inferred (CCC and NCCC) gas profiles (taken from the REXCESS sample) and a cluster mass-dependent gas fraction. Note that our model is calibrated with X-ray observables within $R_{500}$. More work would be needed to extrapolate the model to larger cluster radii that are characterized by an increased complexity, which manifests itself in a larger kinetic-to-thermal pressure support, an increased level of density clumping, as well as cluster asphericity and ellipticity. In our model, we assign a (cluster mass-dependent) gas density profile to each DM halo in our sample and sort it into NCCC/CCC populations according to a dynamical disturbance parameter that is calculated from the DM distribution. Applying the model to our sample of cluster haloes, we obtain volume-limited mock catalogues for the thermal (SZ and X-ray) cluster emission. Our mock catalogues match the observed XLF as well as the $L_{X,\text{bd}}-M_{500}$, $Y_{X}-M_{500}$ and $Y_{SZ}-M_{500}$ relations well.

However, there are some deviations among the different observational scaling relations and our model, which may either point to observational sample selection effects that are not accounted for or missing complexity of our model. This model was specifically constructed to provide a reliable description of the gas density, which necessarily implies a great match of the resulting mock X-ray observables to data (scaling relations and luminosity functions), as well as to the low redshift and massive cluster sample probed by Planck. However, we note that our model has a slightly shallower slope of the $Y_{SZ}-M_{500}$ relation, which implies that the X-ray inferred deviations of self-similarity on small scales become weaker on the larger scales probed through the SZ effect. Moreover, our model overpredicts the normalization of the ACT $Y_{SZ}-M_{500}$ relation (at $z = 0.53$) by about 30 per cent. While this offset is still consistent within the 1σ uncertainty intervals of the ACT scaling relation, this could also indicate possible selection effects of the different cluster samples or alternatively points to a deviation from the assumed self-similar redshift evolution.

In the companion Paper II, we additionally present a model for the radio and gamma-ray emission as a result of hadronic CR interactions with the ICM. We provide cosmologically complete multifrequency mock catalogues for the (non-)thermal cluster emission at different redshifts and make these catalogues publicly and freely available on-line through the MultiDark data base (www.multidark.org). Our mock catalogues are based on density profiles that represent the average cluster population of cool core and non-cool core systems (while we account for scatter in the gas mass fractions, i.e. the normalization of the profiles). As a result, our model does not fully exploit the true variance across the average profile shapes which may result in a limited variance of thermal cluster observables. Nevertheless, the mock catalogues will allow quantitative comparisons to future hydrodynamical simulations and forecasts for future surveys. We emphasize, however, that the catalogues are not suited for detailed cosmological studies in their (present) published form, which do not address any survey response functions nor provide light-cone mock catalogues. However, future surveys should be able to test the underlying assumptions of our modelling approach, which is based on X-ray observations of clusters at low redshift ($z < 0.2$) and adopts self-similar redshift evolution for extrapolating to higher redshifts. We hope that the community can make valuable use of these catalogues in synergy with the future radio, X-ray and gamma-ray data.

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REFERENCES

Battaglia N., Bond J. R., Pfrommer C., Sievers J. L., Sijacki D., 2010, ApJ, 725, 91
Battaglia N., Bond J. R., Pfrommer C., Sievers J. L., 2012a, ApJ, 758, 74
Battaglia N., Bond J. R., Pfrommer C., Sievers J. L., 2012b, ApJ, 758, 75
Battaglia N., Bond J. R., Pfrommer C., Sievers J. L., 2013, ApJ, 777, 123
Böhringer H. et al., 2002, ApJ, 566, 93
Brüggen M., Kaiser C. R., 2002, Nature, 418, 301
Capelo P. R., Coppi P. S., Natarajan P., 2012, MNRAS, 422, 686
Cappelluti N. et al., 2011, Mem. Soc. Astron. Ital. Suppl., 17, 159
Cavagnolo K. W., Donahue M., Voit G. M., Sun M., 2009, ApJS, 182, 12
Chen Y., Reiprich T. H., Böhringer H., Ikke Y., Zhang Y.-Y., 2007, A&A, 466, 805
Churazov E., Brüggen M., Kaiser C. R., Böhringer H., Forman W., 2001, ApJ, 554, 261
Croston J. H. et al., 2008, A&A, 487, 431
Dubois Y., Devriendt J., Slyz A., Teyssier R., 2012, MNRAS, 420, 2662
Ebeling H., Edge A. C., Fabian A. C., Allen S. W., Crawford C. S., Boehringer H., 1997, ApJ, 479, L101
Enßlin T., Pfrommer C., Miniati F., Subramanian K., 2011, A&A, 527, A99
Gaspari M., Brighenti F., Temi P., 2012, MNRAS, 424, 190
Guo F., Oh S. P., 2008, MNRAS, 384, 251
Hasselfield M. et al., 2013, J. Cosmol. Astropart. Phys., 7, 8
Hu W., Kravtsov A. V., 2003, ApJ, 584, 702
Hudson D. S., Mittal R., Reiprich T. H., Nulsen P. E. J., Andernach H., Sarazin C. L., 2010, A&A, 513, A37
Jenkins A., Frenk C. S., White S. D. M., Colberg J. M., Cole S., Evrard A. E., Couchman H. M. P., Yoshida N., 2001, MNRAS, 321, 372
Kaiser N., 1986, MNRAS, 222, 323
Kravtsov A. V., Holtzman J., 1997, preprint (astro-ph/9712217)
Kravtsov A. V., Klypin A. A., Khokhlov A. M., 1997, ApJS, 111, 73
Kravtsov A. V., Vikhlinin A., Nagai D., 2006, ApJ, 650, 128
Kulsrud R., Pearce W. P., 1969, ApJ, 156, 445
Lau E. T., Kravtsov A. V., Nagai D., 2009, ApJ, 705, 1129
Loewenstein M., Zweibel E. G., Begelman M. C., 1991, ApJ, 377, 392
McNamara B. R., Nulsen P. E. J., 2007, ARA&A, 45, 117
McNamara B. R., Nulsen P. E. J., 2012, New J. Phys., 14, 055023
Mantz A., Allen S. W., Rapetti D., Ebeling H., 2010a, MNRAS, 406, 1759
Mantz A., Allen S. W., Ebeling H., Rapetti D., Drlica-Wagner A., 2010b, MNRAS, 406, 1773
Nagai D., Lau E. T., 2011, ApJ, 731, L10
Ostriker J. P., Bode P., Babul A., 2005, ApJ, 634, 964
Pfrommer C., 2013, ApJ, preprint (arXiv:1303.5443)
Planck Collaboration et al., 2013a, A&A, 550, A131
Planck Collaboration et al., 2013b, A&A, preprint (arXiv:1303.5080)
Prada F., Klypin A. A., Cuesta A. J., Betancort-Rijo J. E., Primack J., 2012, MNRAS, 423, 3018
Pratt G. W., Croston J. H., Arnaud M., Böhringer H., 2009, A&A, 498, 361
Puchwein E., Sijacki D., Springel V., 2008, ApJ, 687, L53
Reiprich T. H., Böhringer H., 2002, ApJ, 567, 716
Riebe K. et al., 2013, Astron. Nachr., 334, 691
Röttgering H. et al., 2012, A&A, 32, 557
Ruszkowski M., Begelman M. C., 2002, ApJ, 581, 223
Sanderson A. J. R., O’Sullivan E., Ponman T. J., 2009, MNRAS, 395, 764
Sarazin C. L., 1988, X-Ray Emission from Clusters of Galaxies. Cambridge Univ. Press, Cambridge
Sijacki D., Springel V., Di Matteo T., Hernquist L., 2007, MNRAS, 380, 877
Sijacki D., Pfrommer C., Springel V., Enßlin T. A., 2008, MNRAS, 387, 1403
Sun M., Voit G. M., Donahue M., Jones C., Forman W., Vikhlinin A., 2009, ApJ, 693, 1142
Vazza F., Brüggen M., Gheller C., 2013, MNRAS, 428, 2366
Voit G. M., 2005, Rev. Modern Phys., 77, 207
Wiener J., Oh S. P., Guo F., 2013, MNRAS, 434, 2209
Zandanel F., Pfrommer C., Prada F., 2014, MNRAS, 438, 124 (Paper II)

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