Thermal and non-thermal traces of AGN feedback: results from cosmological AMR simulations

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Accepted 2012 October 12. Received 2012 October 12; in original form 2012 July 8

ABSTRACT

We investigate the observable effects of feedback from active galactic nuclei (AGN) on non-thermal components of the intracluster medium (ICM). We have modelled feedback from AGN in cosmological simulations with the adaptive mesh refinement code ENZO, investigating three types of feedback that are sometimes called quasar, jet and radio mode. Using a small set of galaxy clusters simulated at high resolution, we model the injection and evolution of cosmic rays, as well as their effects on the thermal plasma. By comparing both the profiles of thermal gas to observed profiles from the ACCEPT sample and the secondary $\gamma$-ray emission to the available upper limits from Fermi, we discuss how the combined analysis of these two observables can constrain the energetics and mechanisms of feedback models in clusters. Those modes of AGN feedback that provide a good match to X-ray observations yield a $\gamma$-ray luminosity resulting from secondary cosmic rays that is about 10 times below the available upper limits from Fermi. Moreover, we investigate the injection of turbulent motions into the ICM from AGN, and the detectability of these motions via the analysis of line broadening of the Fe XXIII line. In the near future, deeper observations/upper limits of non-thermal emissions from galaxy clusters will yield stringent constraints on the energetics and modes of AGN feedback, even at early cosmic epochs.

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

1 INTRODUCTION

Radiative cooling of gas in galaxy clusters is so efficient that most of the hot gas phase in their core ought to be removed on a timescale smaller than the lifetime of the system, producing an inward motion of the cooling gas, a ‘cooling flow’ (e.g. Fabian, Nulsen & Canizares 1984). However, dramatic cooling flows are not observed in real clusters, and additional non-gravitational heating mechanisms are likely to keep gas on a higher adiabat (e.g. Kaiser 1991; Ponman, Cannon & Navarro 1999; Lloyd-Davies, Ponman & Cannon 2000). It is largely agreed that active galactic nuclei (AGN) are a viable source of energy available for the self-regulation of galaxy clusters. Observations show that the energy associated with AGN in clusters is in most cases sufficient to balance radiative losses in the intracluster medium (ICM; e.g. McNamara & Nulsen 2007, and references therein). However, it is less clear how the energy is released from the compact (<kpc) region surrounding the central supermassive black hole (BH), to the ~10–100 kpc cooling radius. Very similar problems are encountered in elliptical galaxies (e.g. Sarazin & White 1987; Ciotti & Ostriker 1997; Brighenti & Mathews 2000; Ciotti & Ostriker 2012). For clusters, an important issue is whether most of the energy input from AGN (or galactic winds) to the ICM has occurred much before the assembly of the clusters via ‘pre-heating’ (e.g. Bialek, Evrard & Mohr 2001; Brighenti & Mathews 2001; Tozzi & Norman 2001; McCarthy et al. 2004), or at a low redshift within already formed clusters (e.g. Binney & Tabor 1995; Churazov et al. 2001; Brüggen & Kaiser 2002). The first mechanism requires a lower energy budget, with total energies $\lesssim 10^{62}$ erg (McCarthy et al. 2008), while the second possibility requires energies in excess of $\sim 10^{63}$–$10^{64}$ erg (Mathews & Guo 2011b). However, there is ample evidence for strong AGN outflows in cool-core clusters (e.g. McNamara & Nulsen 2007, 2012).

Theoretical work suggests that the real evolution of heating in clusters might be a combination of both (Brighenti & Mathews 2006; McCarthy et al. 2008; Vazza 2011; Dubois et al. 2012; Short, Thomas & Young 2012).
Quasar-induced outflows at high redshift, possibly following mergers of gas-rich galaxies, have been observed (e.g. Nesvadba et al. 2006; Bhattacharyya, Di Matteo & Kosowsky 2008; Dunn et al. 2010). At lower redshift, the mechanical work done by X-ray cavities on the surrounding ICM may represent another viable mechanism for heating and mixing the ICM (e.g. David et al. 2001; McNamara & Nulsen 2007, 2012). Additional mechanisms can modify the energy requirements of AGN feedback, by providing complementary heating/mixing on various scales. The heating from Alfvén waves in cosmic rays (CRs) enriched bubbles, and heating from Coulomb losses of CRs and the surrounding thermal ICM, is an additional interesting topic of research (Loewenstein, Zweibel & Begelman 1991; Colafrancesco, Dar & De Rújula 2004; Guo & Oh 2008; Sijacki et al. 2008; Fujita & Ohira 2011; Mathews & Guo 2011a).

Thermal conduction can somewhat reduce the energy budget that central AGN have to provide in order to stem cooling flows (e.g. Bertschinger & Melhuish 1986; Bregman & David 1988; Narayan & Medvedev 2001). Magnetorotational instabilities and heat-flux driven instabilities in the weak and anisotropic cluster magnetic field have been proposed to reduce the cooling of gas (e.g. Quataert 2008; McCourt et al. 2011). Finally, also major mergers have been suggested as a viable mechanism to reduce the cooling catastrophe, even if the real efficiency of this mechanism is controversial (Poole et al. 2006; Burns et al. 2008).

Cosmological simulations with radiative cooling, star formation and galactic winds are unable to reproduce the observed profiles of gas temperature, metallicity and entropy in the ICM (e.g. Kravtsov & Borgani 2012, for a recent review). The most powerful feedback from AGN has been studied with cosmological simulations in the recent past. Several groups successfully implemented a treatment of thermal AGN feedback in cosmological GADGET simulations (e.g. Dalla Vecchia et al. 2004; Sijacki & Springel 2006; Sijacki et al. 2007; Fabjan et al. 2010; McCarthy et al. 2010). In the aforementioned papers, the growth of BHs at the centres of galaxies is followed using sink particles, and the energy release from each BH follows from the Bondi–Hoyle accretion rate (‘quasar’ mode). The energy emitted by the AGN is released by heating up smoothed particle hydrodynamics (SPH) particles surrounding the surrounding ICM. Similar methods have been implemented in adaptive mesh refinement (AMR) grid simulations by Cattaneo & Teyssier (2007) and Teyssier et al. (2011) in the RAMSES code. The creation of ‘bubbles’ inflated by AGN during their ‘radio mode’ was simulated by Dalla Vecchia et al. (2004) and Sijacki & Springel (2006) in GADGET. In this case, the energy released by the BH is deposited within pairs of bubbles in the form of thermal energy or CR energy, and exerts mechanical work $PdV$ on the surrounding ICM while buoyantly rising in the cluster atmosphere. Other models of mechanical feedback from AGN have also been implemented, by assigning a ‘wind’ drift velocity to gas particles surrounding the BH, with velocities in the range of $\sim 10^3$–$10^4$ km s$^{-1}$ (Dalla Vecchia & Schaye 2008; Fabjan et al. 2010). Dubois et al. (2010, 2011) implemented a scheme to follow bipolar kinetic outflows (‘jet’ mode) from simulated AGN in RAMSES, monitoring the growth of BHs using the same set-up of Teyssier et al. (2011). In the framework of galaxy formation studies, run-time models of radiative and kinetic feedback from AGN in galaxy simulations have been developed by Kim et al. (2011) in ENZO simulations, and by Oppenheimer & Davé (2006) and Gabor et al. (2011) in GADGET simulations.

To date, however, little attention has been paid to the amount of non-thermal energy deposited in the ICM by the various feedback mechanisms. This is an important aspect, since non-thermal emission from galaxy clusters can offer a complementary way of testing and falsifying feedback models. Once accelerated, CR hadrons can accumulate in galaxy clusters (Berezinsky, Blasi & Ptuskin 1997) and produce a non-thermal component that could be detected by $\gamma$-ray observations (e.g. Ackermann et al. 2010). Secondary particles are continuously injected into the ICM via proton–proton collisions, possibly leading to detectable synchrotron radiation (e.g. Blasi & Colafrancesco 1999; Dolag & Enßlin 2000). The combined analysis of radio observations and $\gamma$-ray upper limits, however, presently suggests that most of the observed large-scale radio emission in clusters cannot be due to secondary electrons, based on theoretical estimates of the required total energy in CRs (Brunetti et al. 2007; Brunetti 2009; Donnert et al. 2010b), and to the required values of the magnetic field in the ICM, in conflict with observations (Brunetti et al. 2009; Bonafede et al. 2010; Donnert et al. 2010a; Bonafede et al. 2011; Jeltema & Profumo 2011).

Therefore, the detection or lack of non-thermal emission from cluster centres may inform us about the energy budget of non-thermal particles, and of the history and modality of previous heating episodes in the ICM. In addition, CR particles may have an important dynamical effect on the ICM (e.g. Brunetti & Lazarian 2011b; Ruszkowski & Oh 2011), and they can also affect the evolution of X-ray cavities powered by AGN jets (e.g. Mathews & Brighenti 2007; Guo & Oh 2008; Sijacki et al. 2008; Mathews & Guo 2011a).

In this work we study the observable non-thermal features related to AGN feedback models in a cosmological framework. A few single-object simulations have been used to investigate the role of CR feedback in stopping cooling flows (Guo & Oh 2008; Fujita & Ohira 2011, 2012). However, the acceleration (and re-acceleration) of CRs at shocks triggered by AGN, as well as at merger and accretion shocks, has been neglected in previous works.

To our knowledge, the present study is the first in which such detailed CR physics (e.g. particle acceleration, reduced thermalization at the sub-shock, pressure feedback of CRs and effective adiabatic index of the baryon gas) as well as variety of AGN feedback models (quasar, jet and bubble modes) have been applied to cosmological simulations.

2 NUMERICAL METHODS

We have produced cosmological cluster simulations with the AMR code ENZO. On the basis of the public 1.5 version of ENZO we have implemented our methods to model the evolution and feedback of CR particles injected at shock waves (Vazza et al. 2012a), as well as our (simplified) implementations of energy release from AGN. ENZO is a grid and AMR code using the piecewise parabolic method (PPM) to solve the equations of hydrodynamics, originally written by Bryan et al. (1995) and developed by the Laboratory for Computational Astrophysics at the University of California in San Diego (Norman et al. 2007; Collins et al. 2010).¹

The detailed description of our modules for CR physics and AGN feedback are presented in Section 2.1. In all runs in this paper, we adopted radiative cooling for a fully ionized H–He plasma with a constant metallicity of $Z = 0.3Z_\odot$, and a cooling function with a cut-off at $T = 10^4$ K (Sarazin & White 1987), as in the public version of ENZO, while the re-ionization background due to the ultraviolet (UV) radiation from early stars and AGN is modelled by keeping a gas temperature floor ($\gtrsim 2 \times 10^4$ K) in the redshift range $4 \leq z \leq 7$ (as in Vazza et al. 2010a).

¹ http://lca.ucsd.edu

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We did not include star formation and feedback through winds or supernovae in these runs, thereby reducing the complexity and memory usage of the code. Hydrodynamical simulations suggest that while supernovae are important to reproduce the observed metal distribution of the ICM, they do not have a significant impact on the thermal history of the ICM on large scales (e.g. Short et al. 2012).

For the simulations presented here, we assumed a ‘concordance’ cold dark matter (LCDM) cosmology with \( \Omega_0 = 1.0, \Omega_b = 0.0441, \Omega_{\text{DM}} = 0.2139, \Omega_{\Lambda} = 0.742 \), Hubble parameter \( h = 0.72 \) and a normalization for the primordial density power spectrum \( \sigma_8 = 0.8 \).

### 2.1 Cosmic ray physics

The basic methods to model the injection, advection and pressure feedback of CRs in our ENZO runs are explained in detail in Vazza et al. (2012a). We assume that CRs are injected at shocks with an acceleration efficiency, \( \eta(M) \), that only depends on the Mach number, \( M \), which is given by diffusive shock acceleration (e.g. Bell 1978; Blandford & Ostriker 1978; Drury & Voelk 1981; Kang & Jones 1990; Ellison, Baring & Jones 1995; Malkov & O’C Drury 2001; Kang & Jones 2007; Caprioli 2012). New CR energy is injected in the system by multiplying the energy flux through each shocked cell by the time step and the spatial resolution at the AMR level-1, respectively. To ensure energy conservation the thermal energy in the post-shock region is reduced proportionally at run-time. The dynamics of the mixture of gas and CRs within each cell follows the total effective pressure of the two, \( P_{\text{eff}} = P_g + P_{\text{cr}} = \rho (\gamma - 1) e_g + (\gamma_{\text{cr}} - 1) e_{\text{cr}} \), where \( \gamma = 5/3, \gamma_{\text{cr}} = 4/3, e_g \) is the gas energy density and \( e_{\text{cr}} \) is the CR-energy density. The dynamical feedback of CR pressure is treated in the Riemann solver by updating the gas matter fluxes in the in 1D sweeps along the coordinate axes and using the effective gamma factor \( \gamma_{\text{eff}} = \frac{\gamma_{\text{cr}}}{\gamma_{\text{cr}} - 1} \), for the computation of the local sound speed in cells.

As in Vazza et al. (2012a), we use the relativistic value of \( \gamma_{\text{cr}} = 4/3 \) everywhere, which corresponds to the flattest possible momentum spectrum of CRs, through \( \gamma_{\text{cr}} = q/3 \) [with \( f(p) \propto p^{-q} \) and \( q = 4 \) for \( \gamma_{\text{cr}} = 4/3 \)]. Fixing the value of \( \gamma_{\text{cr}} \) within the simulated volume is an unavoidable assumption of the two-fluid model adopted here. However, once the CR-energy density is specified, the CR pressure depends only weakly on the spectral shape of \( f(p) \) and on the cut-off of the spectrum (e.g. Jones & Kang 1993; Jubelgas et al. 2008).

To model the injection of CRs at each shocked cell, we developed a run-time shock finder based on pressure jumps, similar to Ryu et al. (2003). At each time step, we flag cells with a negative 3D divergence, \( \nabla \cdot \mathbf{V} < 0 \), and with concordant local gradients of temperature and entropy, \( \nabla S \cdot \nabla T > 0 \) (e.g. Ryu et al. 2003). The local Mach number is computed by inverting standard Rankine–Hugoniot jump conditions for gas pressure. This method can run in either fixed grid resolution or AMR mode in ENZO runs, and compares very well with the shock-finding methods we develop elsewhere (Vazza, Brunetti & Gheller 2009b). Compared to our first paper on this subject (Vazza et al. 2012a), we add the treatment of several additional physical processes that are listed below.

![Figure 1. Acceleration efficiency of CRs as a function of Mach number for different pre-existing ratios of \( P_{\text{cr}}/P_g \) in the pre-shock region. From black to red, the different lines show the acceleration efficiency for \( P_{\text{cr}}/P_g = 0.0, =0.06, =0.12, 0.18, =0.24 \) and =0.3.](https://academic.oup.com/mnras/article-abstract/428/3/2366/1070985)
CR-energy spectrum. Since this information is not readily available in the two-fluid model, we must assume an approximate steady-state spectrum for the CR-energy distribution. We fixed a spectral index of $\alpha = 2.5$ for the particle energy and computed the total Coulomb and hadronic loss rates as a function of the ICM density and of $E_{\text{cr}}$ for each cell, as in Guo & Oh (2008):

$$\Gamma_{\text{coll}} = -\xi \frac{n_e}{\text{cm}^{-3}} \frac{E_{\text{cr}}}{\text{erg cm}^{-3}} \text{erg s}^{-1} \text{cm}^{-3},$$

(2)

where $n_e \approx n$ is the electron number density, and $\xi \approx 7.51 \times 10^{-16}$ is the coefficient for all collisional energy loss terms. In hadronic collisions, only $\approx 1/6$ of the inelastic energy goes into secondary electrons (Colafrancesco et al. 2004; Guo & Oh 2008). The energy-dominating region of CR electrons ($\gamma \approx 10^5$) will heat the ICM through Coulomb interactions, plasma oscillations and excitation of Alfven waves (e.g. Guo & Oh 2008). Therefore, we can assume that these secondary electrons lose most of their energy through thermalization and thus heat the ICM. Similar to equation (2), the heating rate of the ICM through Coulomb and hadronic collisions can be computed as

$$\Gamma_{\text{heat}} = \xi_e \frac{n_e}{\text{cm}^{-3}} \frac{E_{\text{cr}}}{\text{erg cm}^{-3}} \text{erg s}^{-1} \text{cm}^{-3},$$

(3)

where $\xi_e = 2.63 \times 10^{-16}$ (Guo & Oh 2008). In our simulations with radiative cooling and AGN feedback, the rate of energy loss due to these collisions is extremely small, typically $\approx 10^{-3}$ to $10^{-4}$ of $E_{\text{cr}}$ or $e_{\text{c}}$ during the time step at each AMR level. This allows us to use a simple first-order integration to compute the energy losses of CRs (and the corresponding gas heating rate) at run-time.

In our previous work (Vazza et al. 2012a), we did not include hadronic and Coulomb losses. In general, modelling this process at run-time decreases the CR energy by a factor of $\approx 10$ within cluster cores, while yielding identical results for the remaining cluster volume compared to runs that neglect losses.

### 2.2 Models of feedback from AGN

In Vazza (2011), we implemented a simple model of AGN feedback in ENZO, via injection of thermal energy at the opposite sides of the cooling region of galaxy clusters. Here, we explore more complex recipes of energy feedback between the cold gas and the surrounding ICM, allowing also for a direct input of CR energy from AGN.

At each time step, the identification of a suitable location of the central supermassive BH is based on the simple measure of local gas overdensity. First, we flag cells hosting a gas density exceeding a given threshold, $n \geq n_{\text{BH}}$, and then we select as active ‘AGN cells’ only the maxima within cubic regions of size $\approx 1 \text{ Mpc} h^{-1}$. Based on more detailed modelling of BH growth using sink particles (Sijacki et al. 2007; Teyssier et al. 2011; Martizzi et al. 2012), we tuned the threshold value to excite AGN feedback to $n_{\text{min}} \approx 10^2 \text{ cm}^{-3}$. The use of this threshold is motivated by the fact that in our fiducial set-up (peak resolution of 25 kpc $h^{-1}$ per cell) the mass enclosed in a cell with $n = 10^1$ to $10^2 \text{ cm}^{-3}$ is $\approx 10^{10}$ to $10^{11} \text{ M}_\odot$. This is the typical gas mass surrounding BHs of $M_{\text{BH}} \approx 10^6$ to $5 \times 10^7 \text{ M}_\odot$, which are commonly hosted inside the masses of galaxy clusters and groups (e.g. Sijacki et al. 2007; Teyssier et al. 2011; Martizzi et al. 2012).

In the following, we will refer to the cells exceeding this density threshold and powering energy feedback as ‘AGN cells’.

We have implemented three modes of AGN feedback: a ‘quasar’ mode (i.e. thermal output of energy from AGN, Section 2.2.1), a ‘jet’ mode (i.e. kinetic energy output from bipolar jets around AGN, Section 2.2.2) and a ‘radio’ mode (i.e. creation of buoyant bubbles in pressure equilibrium with the ICM, Section 2.2.3).

Once the feedback mode is specified, the only parameters that must be set are (a) the initial redshift for the start of AGN feedback ($z_{\text{AGN}}$) and (b) the energy release of each single AGN event, $E_{\text{AGN}}$. In the case of ‘quasar’ and ‘jet’ modes this directly measures the energy we provide for each burst of either thermal or kinetic energy, while for the ‘bubble’ feedback this represents the estimated total energy released to the ICM by the creation of bubbles with internal pressure $P_{\text{bb}}$ and volume $V_{\text{bb}}$, $E_{\text{AGN}} \approx 3P_{\text{bb}}V_{\text{bb}}/2$ (e.g. Scannapieco & Brüggen 2008). Even if jets and radio bubbles are associated with the same type of AGN feedback (e.g. McNamara & Nulsen 2007, 2012), in our study they are considered as alternative scenarios. This allows us to distinguish the CR effects of buoyancy and impulsive kinetic feedback in a clearer way.

In a preliminary set of tests (see Appendix A) we explored various recipes for the implementation of feedback modes in one reference cluster, before varying the efficiencies in the whole set of clusters.

Here, however, we will discuss only the ‘fiducial’ subset of parameters for which each implementation of feedback modes showed the best performance. While the range of spatial resolution achieved in our runs is probably not sufficient to study specific small-scale features associated with each AGN mode (e.g. the morphology of jets or rising bubbles), our resolution and physical set-up are suitable for studying the large-scale features of CRs in the ICM.

#### 2.2.1 Thermal feedback from AGN

A significant fraction of the energy emitted from AGN can thermally couple to the surrounding gas. One can define efficiencies such that the energy added in time $\Delta t$ is

$$\Delta E_{\text{AGN},\theta} = \epsilon \epsilon_t M_{\text{BH}} c^2 \Delta t,$$

(4)

where $\epsilon_t \approx 0.1$ is the bolometric radiative efficiency for a Schwarzschild BH (Shakura & Sunyaev 1973), $M_{\text{BH}}$, and $\epsilon_t$ is the coupling efficiency with the thermal gas, which is usually assumed to be in the range of $\epsilon_t \approx 0.05$–0.15 in order to fit the observed $M_{\text{BH}}$ versus $\sigma_v$ relation (e.g. Di Matteo et al. 2005; Booth & Schaye 2009; Yang et al. 2012). This thermal coupling between the AGN and the surrounding ICM is usually called ‘quasar’ feedback, which may be a mechanism for pre-heating of the ICM (McCarthy et al. 2004, 2008; Lapi, Cavaliere & Menci 2005; Sijacki, Springel & Haehnelt 2009; Lapi, Fusco-Femiano & Cavaliere 2010). In addition, quasar-induced outflows at high redshift, possibly following mergers of gas-rich galaxies, have been observed in many cases (e.g. Nesvadba et al. 2006; Bhattacharya et al. 2008; Dunn et al.

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2 This choice of $\alpha$ corresponds to a Mach number of $M = 3$ at the particle injection. On average, this represents the typical injection spectra of particles accelerated at powerful merger shocks in cosmological simulations, which are dominant sources of thermalization and CR injection within clusters (e.g. Vazza et al. 2011b, and references therein).
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2010). Similar to McCarthy et al. (2010) and Teyssier et al. (2011), when we detect cells with $n \geq n_{\text{min}}$, we release the thermal energy, $E_{\text{AGN}}$, adding to the total and internal gas energy inside cells at the highest available AMR level.

This implementation of quasar feedback is only an approximation of the true physical processes at play, i.e. the launching of strong winds due to the radiation pressure of photons from the accretion disc. This is unavoidable, given that our best resolution is orders of magnitude larger than the theoretical accretion disc region, and also given the difficulty of modelling the radiative transfer of photons from the accretion region.

Our choice of a minimum gas density $n_{\text{min}} = 10^{-2} \text{ cm}^{-3}$ selects the typical environment of massive BHs within clusters and groups. Furthermore, we assume an energy output similar to most theoretical models, without actually measuring the accretion power of BHs at run-time. This is different from simulations where the mass growth of BHs is modelled using sink particles, which enables an accurate reconstruction of the BH matter accretion rate at run-time. This is not possible in our case. Our approach is only a first step to include the effects of AGN feedback in our version of the code, and it allows us a fast and efficient study of AGN modes.

2.2.2 Kinetic feedback from AGN

The innermost ICM can be affected by the injection of kinetic energy through bipolar jets originating from the AGN (e.g. Binney & Tabor 1995; Ciotti & Ostriker 2012). This energy can be thermalized by impacting on the ICM after a short distance from the cluster centre (10–100 kpc; Pope 2009). Gaspari et al. (2011a,b) and Dubois et al. (2010, 2011) recently simulated the mechanical coupling between purely kinetic jets from the AGN and the surrounding ICM in the cooling region.

In this model each of the two jets is initialized as a pure input of kinetic energy density $E_{\text{AGN}} = 1/2 \rho v_{\text{jet}}^2$, with velocity, $v_{\text{jet}}$, pointing radially outwards from the cluster centre. Even if in our version of ENZO the launching direction of the jets is set by a random selection of coordinate axes, in this work we keep the jet axis fixed. In this way, velocity effects related to the direction of jet launching can easily be detected (Section 3.4). Every time a jet is generated, we modify the gas velocity, the total and internal energy at the highest available AMR level in a pair of cells on opposite sides of the gas density peak. The width and the initial extension of the jet are set by the maximum resolution, which is $\sim 10$ times larger than the best resolution available in ‘single-object’ runs (Gaspari et al. 2011a). At our resolution, the equivalent opening angle of each jet is $\sim 30^\circ$–$40^\circ$ with respect to the cluster centre. This is an unavoidable drawback of the fact that in such cosmological runs achieving a much larger resolution is computationally very expensive. However, for the dynamical feedback of jets the most important quantity is the injected kinetic energy, which is similar to simulations at higher resolution, once the different mass load of the jets and launching velocity are considered. Also the initial velocity of our jets (which depends on the typical density of AGN cells, through the total kinetic energy released in the AGN burst) is $\sim 500$–$1000 \text{ km s}^{-1}$, about one order of magnitude lower than the typical velocity of jets in single-object simulations at much higher resolution (Gaspari et al. 2011a,b).

2.2.3 Bubble feedback from AGN

The creation of buoyant bubbles in the ICM inflated by jets requires a spatial resolution ($\sim 0.1$–$1 \text{ kpc}$) beyond what can be achieved in our cosmological runs. For this reason, we created already formed evacuated bubbles around cells hosting an AGN, similar to Scannapieco & Brüggen (2008). The bubbles are created in (approximate) pressure equilibrium with the surrounding ICM, by decreasing the gas density inside the cells by $\rho' = \Delta \rho_0 \rho$, and correspondingly increasing the thermal energy in order to conserve the original gas pressure. During run-time, this modification is performed over a single time step of the simulation, at the highest available AMR level. This obviously leads to a loss of mass in these cluster runs. The simulations show that on average this loss amounts to $\sim 5$–$10$ per cent of the gas mass by the end of the simulation.

The initial underdensity of the bubbles is set by energy conservation inside the bubbles, after that $E_{\text{AGN}}$ is added to the gas and CR energy within the same volume. For the range of $E_{\text{AGN}}$ and $n_{\text{min}}$ adopted in this work, the underdensity inside the bubbles is typically 0.1–0.01. The bubbles are generated as a pair of cubic blocks of $2^3$ cells, at the distance of two cells from the cluster centre. This is a very crude approximation and is expected to lead to expedient numerically mixing of the thermal energy.

In principle, we can also allow for the presence of CRs injected by the AGN, parameterized by $\Phi_{\text{CR}} = E_{\text{AGN}}/E_{\text{FWHM}}$ of the total injected energy, similar to Sijacki et al. (2008). In this case the energy of the bubbles is conserved also by modifying the effective adiabatic index of the mixture of gas+CRs (as in Vazza et al. 2012a). However, in the main body of this paper we only refer to purely thermal bubbles. We present a few results with gas+CRs inflated bubbles in Appendix A (the results, however, are not significantly different).

3 RESULTS

The results discussed in the main part of this paper have been produced considering the following physical mechanisms: (a) pure cooling; (b) cooling and thermal feedback by AGN from $z \leq 4$, with a fixed energy release per event of $E_{\text{AGN}} = 10^{59}$ erg (or also $10^{60}$ erg in the case of E1 and E5A); (c) cooling and kinetic energy feedback by AGN from $z \leq 4$, with a fixed energy release per event of $E_{\text{AGN}} = 10^{59}$ erg; (d) cooling and energy feedback from buoyant bubbles injected by AGN from $z \leq 4$, with an approximate energy per event of $E_{\text{AGN}}$ $\sim 10^{59}$ erg. With the above implementations, we resimulated four clusters in the mass range $10^{14} \leq M \leq 10^{15} \text{ M}_\odot$.

The list of the most important parameters of all ‘fiducial’ models investigated in the article is given in Table 1. The first model (pure cooling) obviously produces strong cooling flows in all systems. In this work, this model is therefore regarded only as a standard reference to assess the role of each feedback model.

In order to achieve the largest possible dynamical range inside the volume where each cluster forms, the four clusters were resimulated at high spatial and DM mass resolution starting from parent simulations at lower resolution and adding nested initial conditions.

| ID | Cooling | $E_{\text{AGN}}$ (erg) | Feedback mode |
|----|---------|------------------------|---------------|
| Cooling | Yes | 0 | No |
| Quasars | Yes | $10^{59}$ | Thermal, $T_{\text{AGN}} \sim 5 \times 10^7$ K |
| Quasars2 | Yes | $10^{60}$ | Thermal, $T_{\text{AGN}} = 5 \times 10^8$ K |
| Jets | Yes | $10^{59}$ | Kinetic, $v_{\text{jet}} \sim 750 \text{ km s}^{-1}$ |
| Bubbles | Yes | $10^{59}$ | Buoyant, $\delta_{\text{bbl}} \sim 0.05$ |
Table 2. Main parameters of the clusters simulated in this work. Column 1: identification name. Column 2: total (gas+DM) mass at $z = 0$. Column 3: virial radius ($R_v$). Column 4: dynamical state at $z = 0$. The identification name of each cluster is chosen to be consistent with other works of ours (Vazza et al. 2010a, 2012a). The cluster parameters are referred to the simple non-radiative simulation of each object.

| ID  | $M_{\text{tot}}$ ($\times 10^{14} M_\odot$) | $R_v$(Mpc) | Dynamical state   |
|-----|------------------------------------------|------------|-------------------|
| E1  | 11.2                                     | 2.67       | Post-merger       |
| E5A | 8.2                                      | 2.39       | Merging           |
| H5  | 2.4                                      | 1.70       | Post-merger       |
| H10 | 1.2                                      | 1.20       | Relaxed           |

of increasing spatial and mass resolution (e.g. Abel et al. 1998). Two levels of nested initial conditions were placed in cubic regions centred on the cluster centres. The box at the first level had the size of $\approx 95$ Mpc $h^{-1}$ (with $m_{\text{dm}} \approx 5.4 \times 10^9 M_\odot h^{-1}$ and constant spatial resolution of $\Delta s \approx 425$ kpc $h^{-1}$). The second box had a size of $\approx 47.5$ Mpc $h^{-1}$ (with $m_{\text{dm}} \approx 6.7 \times 10^8 M_\odot h^{-1}$ and constant spatial resolution of $\Delta s \approx 212$ kpc $h^{-1}$). For every cluster run, we identified cubic regions with the size of $\approx 6 R_v$ (where $R_v$ is the virial radius of clusters at $z = 0$, calculated in lower resolution runs), and allowed for three additional levels of mesh refinement, achieving a peak spatial resolution of $\Delta s \approx 25$ kpc $h^{-1}$ (in the following, we will refer to this subvolume as to the ‘AMR region’). From $z = 30$ (the initial redshift of the simulation) to $z = 2$, mesh refinement is triggered by gas or DM overdensity. From $z = 2$ an additional refinement criterion based on 1D velocity jumps (Vazza et al. 2009a) is switched on. This second AMR criterion is designed to capture shocks and intense turbulent motions in the ICM out to the clusters outskirts. Shocks and turbulence are analysed in the next sections (Sections 3.2–3.4). In addition, our test with ENZO has shown that this composite AMR criterion better captures physical mixing motions in the ICM, and reduces the amount of numerical mixing, with important consequences in the amount of cold gas within the cluster volume (Vazza 2011). However, this method is computationally much more expensive with respect to the gas/DM overdensity criteria alone, and we could afford to run it only in the ‘fiducial’ AGN models (Table 1).

In Appendix A we show the effects of different implementations and energies budget in AGN feedback in the smallest of these systems, using the standard AMR criterion which works on gas/DM overdensity. In the main paper we will study the observable thermal and non-thermal features of the ‘fiducial’ implementation of each feedback mode in our version of ENZO. The parameters of the small cluster sample resimulated with the different recipes of AGN feedback is given in Table 2.

The evolution of gas temperature between $z = 2$ and 0 in cluster H5 (quasar mode) is shown in the panels of Fig. 2. Blast waves triggered by AGN feedback (highlighted by arrows) in the thermal mode drive powerful shocks through the ICM, adding to the pattern of merger and accretion shock waves. We observe that in general only two to three AGN cells are located inside forming clusters at a high redshift, while at a lower redshift only one AGN cell is usually found inside the virial volume. The shocks triggered by AGN feedback are efficient in removing the cold gas phase at $z > 1$, while producing significant amounts of CRs in the forming cluster. Blast waves also cause the expulsion of a significant fraction of the hot gas from the cluster volume, in line with McCarthy et al. (2010).

Figure 2. Time sequence of gas temperature [in units of (K) in the colour coding] for a slice of $5 \times 5$ comoving Mpc $h^{-1}$ and width 25 kpc $h^{-1}$ for run H5 with ‘quasar’ feedback. The arrows point to the locations of recent ‘quasar’ events in the volume. The ‘coarse’ resolution of the first snapshots is due to the fact that we turn on AMR based on velocity jumps at $z = 2$.  

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Figure 3. Time sequence of mass-weighted average gas temperature for a comoving volume of \((5 \text{ Mpc} h^{-1})^3\) in the formation region of cluster H5. We show the results of the three resimulations employing AGN feedback, always with an energy per event of \(E_{\text{AGN}} = 10^{59}\) erg. Horizontal arrows suggest the location of interesting episodes of AGN feedback within the volume.

Fig. 3 shows a comparison of projected gas temperature across the entire AMR region of the same cluster, at three different cosmic epochs. While the large-scale morphology of the cluster is similar in all runs towards the end of the simulation, each feedback mode locally perturbs the ICM in a different way, driving powerful outbursts (or buoyant bubbles) whenever strong cooling causes \(n > n_{\text{min}}\).

In the quasar mode, the final large-scale morphology of the cluster is also affected by the overall action of powerful thermal bursts, and presents a large amount of ejected hot gas outside of the cluster volume. In the jet mode, prominent jets are launched along the horizontal axis, driving powerful shocks \((M \sim 5\text{--}10)\) into the \(\sim 10^5\text{--}10^7\) K cooling gas as well as gas motions along their axis. The bubble mode, on the other hand, has barely detectable effects on the large scale, and is globally similar to a simple pure cooling run (not shown).

Fig. 4 presents a zoomed image of the gas density maps for a slice of \(2 \times 2 \text{ Mpc}^2\) and depth \(25 \text{ kpc} h^{-1}\) for the final configuration of cluster E5A in runs employing AGN feedback. Jets and quasars are not active any more at \(z = 0\) in this run, and no clear features related to their activity can be seen in the innermost cluster region at this redshift. A pair of bubbles, on the other hand, has recently been injected and can be seen as a couple of underdense blobs on opposite sides of the cluster centre (shown by green circles in the image). Other images of active jets and bubbles can be seen in Fig. A1 of Appendix A.

We use phase diagrams for the cells inside the virial volume in order to characterize relevant differences. In Fig. 5 we show the example of phase diagrams for an early cosmic epoch before the cluster formation, \(z = 2\) (top panels), and after the formation of the cluster, \(z = 0.2\) (bottom panels) for the four different feedback modes. The most evident difference between the runs is the absence of the ‘cooling flow’ phase on the lower right part of the diagram, in all runs employing AGN feedback. In the bubble mode, the feedback from buoyant bubbles only affects the high-density regions around the cluster core. At high redshift, the phase diagram is very
Figure 4. Gas density (top panels) for a slice of $2 \times 2 \, \text{Mpc} \, h^{-2}$ and width $25 \, \text{kpc} \, h^{-1}$ across the resimulations of cluster E5A at $z = 0$. The colour coding is $[\rho/\rho_{cr,b}]$ (where $\rho_{cr,b}$ is the baryon critical density). The green circles show the projected location of two bubbles previously injected in the cluster centre.

Figure 5. Phase diagrams of cells within the virial volume of the resimulations of cluster E1 at $z = 2$ (top panels) and at $z = 0.2$ (bottom panels). The colour coding shows the cell-wise pressure ratio between CR and gas within cells; the thick line shows the average trend within each phase diagram.

similar to the pure cooling run, with the exception of the selective removal of gas with $n_{\min} > 10^{-2} \, \text{cm}^{-3}$ cells, which are heated to high temperatures ($> 5 \times 10^7 \, \text{K}$) by the injection of bubbles. On the other hand, in the quasar and jet modes the action of feedback drastically alters the phase diagrams with respect to the pure cooling run. This is particularly evident in the quasar mode at $z = 2$, where a ‘cloud’ of high-temperature cells ($T > 10^7 \, \text{K}$ and $n \sim 10^{-4} \, \text{cm}^{-3}$) is left after the passage of an AGN-driven blast wave. At $z = 0.2$, the ‘cooling’ phase has almost disappeared in jet and quasar feedback, due to the efficient and volume-filling nature of the heating events driven by such powerful mechanisms. In the bubble run the phase diagram is similar to the pure cooling run, with the exception of the $n \sim 10^{-2} \, \text{cm}^{-3}$ regime, where bubbles are injected almost continuously and over cooling is balanced by mixing. This leaves a significant portion of ‘cold’ ($< 10^6 \, \text{K}$) and dense cells in the simulated volume, characterized by large values of $P_{cr}/P_{g}$. 

3.1 X-ray properties

We compare our simulations with the collection of Chandra cluster observations of Cavagnolo et al. (2009), publicly available via the ACCEPT catalogue (http://www.pa.msu.edu/astro/MC2/accept). The catalogue consists of 241 clusters mostly located in the redshift range 0.05 ≥ z ≥ 0.5 and with average central temperatures in the range of 0.5–10 keV. For our comparison we selected a subsample of ~60 objects from the ACCEPT catalogue, with redshifts and average central temperatures compatible with our cluster data set: z ≤ 0.2 and 0.2 ≤ T ≤ 5 keV inside 0.2R200. For further details on the ACCEPT catalogue and set of observations, we refer the reader to Cavagnolo et al. (2009).

In Fig. 6, we show the radial profile of reduced gas entropy4 (K/TSL, where K = TSL/n2/3 and TSL is the spectroscopic-like temperature; Rasia et al. 2005), gas number density, n, and spectroscopic-like temperature for the different feedback modes. The simulated profiles are compared to the profiles of observed clusters, divided by the colour coding into ‘cool-core’ systems if their central entropy is <30 keV cm2 (in blue), or ‘non-cool-core’ systems otherwise (red).

As expected, none of the pure cooling runs can reproduce the observed profiles. In these runs, steep gas density profiles with central values of ~0.1–1 cm−3 and reduced central entropy below ~10 cm2 are found, at odds with observations and in agreement with standard radiative runs (e.g. Li & Bryan 2012, for a recent review). Only cluster E1 is marginally within the range allowed by observations for density and entropy. However, considering that this system has just gone through a strong major merger at (z ∼ 0.25), it cannot be classified as a classical cool-core cluster, as suggested by its gas density and temperature profile. On the other hand, all runs employing AGN feedback yield a much better comparison with observations. Jet and bubble feedback modes produce roughly similar profiles for all clusters: a rather flat entropy profile within the cluster volume. However, episodes of AGN feedback are present by its gas density and temperature profile. On the other hand, all feedback modes used a total amount of energy in the range of 2–9 × 1041 erg, corresponding to ~0.01–0.09 of the total thermal energy of the cluster at z = 0.

Interestingly, by the end of the simulation the higher power AGN mode (EAGN = 1056 erg) used about ~30 per cent less energy than the lower power run (EAGN = 1050 erg), which is ~1/3 of the total energy used in the kinetic feedback mode at a lower power. The total energy budget used in the bubble mode is similar to the quasar mode at the same power per event. We note that in this system the use of AGN feedback is significantly reduced for z > 0.6, due to the onset of large-scale mergers and powerful shock heating within the cluster volume. However, episodes of AGN feedback are present even at later epochs. Overall, a smaller amount of energy from AGN feedback is necessary to balance the catastrophic cooling with purely thermal feedback, or bubbles, compared to kinetic feedback. This is consistent with analytical results of Pope (2009, fig. 1), where it is shown that a higher injection rate of kinetic energy, with respect to thermal energy, is necessary to balance the cooling flow for cluster masses >1013 M⊙. This is because in a massive cluster the critical momentum injection rate needed to overcome the pull of gravity and the surrounding gas pressure in the cluster core is more difficult to reach than the critical injection rate of thermal energy required to overcome the cooling flow via thermal feedback. In addition, the energy release from jets close to the cluster core is very anisotropic, and it becomes more isotropic (due to the driving of shocks) only at a distance of ~100–200 kpc from the core.

Overall, the X-ray properties of our clusters seem consistent with observed low-temperature non-cool-core clusters since the typical internal drop in temperature of cool-core clusters is not observed. On the other hand, in the epoch in which the AGN feedback is triggered in our simulations, the thermal structure of the innermost cluster regions is not compatible with the appearance of typical cool cores either, because the internal drop in temperature is typically much stronger than what is observed. A lack of resolution compared to observations could be responsible for that.

However, we find no evidence of bimodality in the distribution of clusters entropy or gas density in our resimulations, at odds with observations (Cavagnolo et al. 2009; Pratt et al. 2010; Eckert et al. 2012). This might be connected to our coarse sampling of the parameter space of AGN feedback, or may instead call for the implementation of more complex physics in our simulations. However, the investigated sample is too small to address this important issue in detail, and we will leave this for future work.

We illustrate the effects of AGN feedback on the radial distribution of baryon fraction by referring to the relevant example of cluster H5 at z = 0, shown in Fig. 8. As expected, the onset of the cooling flow causes too strong a concentration of baryons inside the cooling radius, clearly at odds with observation (e.g. Ettori et al. 2009; Sun 2012, and references therein). On the other hand, all feedback runs produce a final distribution of gas mass which is more in agreement with observations, showing increasing profiles towards the cluster outer regions (e.g. Ettori et al. 2009; Sun 2012). Approaching R200 the enclosed gas mass fraction is 90–100 per cent of the cosmological baryon fraction. However, the different implementations of feedback produce significantly different and time-dependent features in the profile. In particular, the mechanical action of jets changes the shape of the enclosed baryon fraction in this low-mass system, due to a more recent feedback episode. Similar trends are found in the other systems, provided that the

4 We use the ‘reduced’ entropy, rather than the usual entropy, K = T/n2/3, since this removes the dependence on the host cluster mass (Borgani et al. 2008).
Figure 6. Profiles of reduced gas entropy, gas number density and spectroscopic-like temperature for the simulated clusters (thick lines with different styles) and for observed clusters in the ACCEPT catalogue (Cavagnolo et al. 2009, the red lines are for non-cool-core clusters and the blue are for cool-core clusters). Each row shows the profiles of a different feedback mode. The last row shows the profiles for the quasar mode, with $E_{\text{AGN}} = 10^{56}$ erg per event (only the two most massive clusters are shown).
time-dependent action of jets of this power has a decreasing impact on the shape of the baryon fraction profile moving to larger masses. In the case of bubble feedback, the artificial removal of gas when bubbles are created causes a small deficit of baryons inside the radius. Since the enclosed baryon fraction is very similar (within a few per cent at all radii) to the one obtained with thermal feedback, where the gas mass is conserved instead, we conclude that the loss of baryon mass due to our procedure of generating bubbles is not the leading mechanism of the observed trend.

3.2 Shocks and cosmic rays

Blast waves triggered by explosive AGN feedback (in the quasar or jet mode) inject CRs at $M > 3$ shock waves in the ICM. This can happen before and after the formation of the cluster, as already shown in Fig. 2. These shocks add to the underlying pattern of cosmological shock waves driven by matter accretion, and to the budget of shock-accelerated CRs that are continuously injected into the ICM (Ryu et al. 2003; Pfrommer et al. 2006; Skillman et al. 2008; Vazza et al. 2012a).

Fig. 9 gives an example of the different patterns of shock waves and CR energy in the resimulations of one simulated cluster (we choose here the epoch of $z = 1$, when AGN feedback is still very active). The pure cooling run and the run employing bubble feedback show a pattern of shocks similar to non-radiative runs (Vazza et al. 2012a), with strong accretion shocks enveloping the cluster and a few weaker substructure shocks inside the cluster. The CR energy in these runs is concentrated within the cluster and the filaments of matter being accreted on to it. The resimulations with jets and quasars present a much wider distribution of CR energy, as a result of previous episodes of gas and CR expulsion from the protocluster. In this case, shocks launched by mergers and accretions add to those previously driven by AGN bursts. In general, along the directions of powerful outflows of gas and CRs the location of accretion shock from smooth material is shifted up to several $\sim$ Mpc from the cluster centre. This happens because the release of non-gravitational energy heats the ICM along the outflows, and increases the sound speed there. Very similar trends are found also in the other clusters. This implies that, in general, the impact of feedback on the distribution and amount of CR energy can be significant not only inside clusters, but also in large-scale filaments associated with the cluster.

The differential volume distribution of shock Mach number (measured as explained in Section 2.1) for the same volume of (5 Mpc)$^3$ of Fig. 9 is shown in Fig. 10, for all feedback modes. At the epoch of this output ($z = 1$), we find a systematic deficit of shocks in runs with quasar feedback, simply because shocks have travelled out of the reference volume, and the ICM is overall much hotter with respect.
to pure cooling or bubbles feedback. The run with jets displays a distribution of Mach numbers closer to the pure-cooling case, but it shows a similar deficit of strong shocks inside the reference volume.

In Fig. 11 we show the profiles of the pressure ratio $P_{\text{cr}}/P_g$ for all clusters of the sample. As a reference, we also plot the average pressure ratio obtained with the sample of seven non-radiative cluster runs presented in Vazza et al. (2012a).

In all feedback modes we measure a ratio $P_{\text{cr}}/P_g \sim 0.1$ inside $R_c$, within the range of what we already reported for non-radiative runs employing only CR injection at cosmological shocks (Vazza et al. 2012a). However, large variations are found by comparing pure cooling or feedback runs.

Cooling acts to increase this ratio by removing gas from its hottest phase at all radii. In addition, pure cooling is also found to dramatically increase the loss rate of secondary particles in the centre, up to $\sim 10^{42}$ erg s$^{-1}$ (as shown in Fig. A2 of Appendix A). The heating term from CRs is, however, not sufficient to balance the radiative losses in the innermost ICM, which are usually $\sim 10^{45}$ times larger. Approaching the cluster core we measure $P_{\text{cr}}/P_g \sim 0.5-2$ in the smallest objects, and $\sim 1-10$ in the most massive ones. Unfortunately, our sample of clusters is too small to allow us to infer a trend with the cluster mass. One possible reason for this trend can be, however, numerical: if the maximum spatial resolution is fixed (as in this case) the cooling region of largest structures is better resolved, usually producing a slightly larger gas density peak and a significantly higher cooling rate. This trend in the cooling rate has been reported in a number of works investigating SPH (e.g. Valdarnini 2002; Tornatore et al. 2003) or Eulerian simulations (e.g. Bryan & Norman 1998; Li & Bryan 2012). This trend with radius of the pressure ratio is also similar to what is found also with SPH codes (Pinzke & Pfrommer 2010; Aleksić et al. 2012).

We find that feedback acts to reduce the pressure ratio $P_{\text{cr}}/P_g$ at all radii, this effect being larger inside $R_{200}$. This suggests that although AGN feedback on average triggers the injection of additional CR energy in the cluster core compared to simple radiative runs, its effect is that of reducing the dynamical role of CRs, because the same process also increases the thermal gas pressure. Although AGN feedback has the effect of changing the innermost shape of the profiles of pressure ratio in clusters H5 and H10 (producing a profile more similar to the non-radiative case, with $P_{\text{cr}}/P_g < 0.1$ inside $R_{200}$), the profiles of the pressure ratio in clusters E1 and E5A still show a maximum within the cluster core, with $P_{\text{cr}}/P_g \sim 0.2-0.3$.

This internal shape is opposite to the case of the pure-radiative runs, and seems to be the ‘imprint’ of the early cooling stage of both systems. We verified that indeed this profile is already in place at earliest epochs of cluster formation ($z \sim 1-2$) for both systems. It seems that once that the ‘cooling’ profile had enough time to form, its imprint can hardly be erased by AGN feedback, especially in high-mass systems where, for a given AGN power, it is more difficult to produce an efficient outflow of the CRs previously accumulated. Similar profiles of the CRs to pressure ratio have been reported for single-object simulations of AGN feedback in cooling flow clusters (Guo & Oh 2008; Fujita & Ohira 2011, 2012), suggesting that this may be a stable feature of such physical models. In order to study in detail the mass dependence of $P_{\text{cr}}/P_g$ in cosmology, a much larger cluster sample is required.

In general, it is not straightforward to immediately relate the power released by feedback (as in Fig. 7) to the injected CR energy within the cluster volume. Shocks which follow the most recent event of jet or quasar feedback are surely responsible for the injection of new CR energy inside the cluster, as shown in Fig. 9. This can be seen also in the close correlation between the power per event of AGN feedback and the resulting $P_{\text{cr}}/P_g$ pressure ratio inside clusters in the tests shown in Appendix A (Figs A3–A4). However, the long-term evolution of the simulated ICM and of its balance between CRs and gas energy depends also on other factors, such as the density-dependent secondary losses (Section 2.1.2) and the further evolution of matter accretion from the outer cluster region. Indeed, cooling and feedback do not only affect the cluster core, but also the density distribution in the accreted substructures, causing the release of different pattern of shock waves (e.g. Kang et al. 2007; Pfrommer et al. 2007) and turbulent motions (e.g. Valdarnini 2011). For this reason, it seems not possible to derive a simple prescription to relate the release of feedback energy to the budget of CR energy within clusters at low redshift, once that all competing mechanisms are fully taken into account.

We can compare these values to the available constraints from observations (see also next Section 3.3 for a close comparison with $\gamma$-ray observations). The present upper limits for a large sample of nearby galaxy clusters observed with Fermi imply $P_{\text{cr}}/P_g < 0.05-0.1$ (e.g. Ackermann et al. 2010; Jeltema & Profumo 2011), with a poor dependence on the assumed spectra of CR. Also the limits on the presence of diffuse Mpc-scale radio emission in clusters can be used to constrain secondary electrons and thus the energy density of the primary CR protons (Brunetti et al. 2007; Brown et al. 2011). In this case, the limits depend also on the cluster magnetic field strength and are complementary to those obtained from $\gamma$-rays. In the relevant case of an average magnetic field in clusters of a $\sim \mu$G (Bonafede et al. 2010), radio observations of clusters with no Mpc-scale radio emission suggest that $P_{\text{cr}}/P_g < 0.05 (0.15)$ in the case of a spectrum with an index $\alpha = 2.5 (\alpha = 3)$, while the limits are less stringent for smaller average magnetic fields (Brunetti et al. 2007; Jeltema & Profumo 2011). These limits usually refer to innermost $\sim $ Mpc regions of clusters, where both the number density of thermal protons and the magnetic field are larger. At present no tight constraints are available for the clusters outskirts where the CR contribution might be larger.

Figure 10. Differential distribution of shock Mach numbers as a function of the AGN feedback mode, for the same simulated volume as in Fig. 9.
According to Fig. 11, it seems that all runs with unbalanced cooling produce a ratio $P_{\text{cr}}/P_g$ that is incompatible with radio/γ-ray observations. In runs with AGN feedback, we find a consistency with the above upper limits in the two smallest size clusters, and a significantly larger pressure ratio in the two largest systems (factor of $\sim2$–3 in the centre). However, when the γ-emission of our clusters is directly compared to the available data from Fermi, the results of AGN feedback are below the upper limits. This is because the γ-emission is more sensitive to the density ($\propto n^2$) than to the pressure ratio between CRs and gas ($\propto P_{\text{cr}}/P_g$), and therefore the net effect of AGN in our simulations is that of producing a lower γ-flux compared to upper limits, although producing a large $P_{\text{cr}}/P_g$ in the centre. In the case of radio upper limits, the values of $P_{\text{cr}}/P_g$ in our runs can be better reconciled with radio data if the average spectrum of CRs is $\alpha \sim 3$ (or steeper). As we will discuss in Section 3.3, this is actually the case of most of the CR energy found in our cluster runs.

### 3.3 γ-ray flux

CR protons colliding with thermal protons of the ICM produce secondary γ-ray emission (Dennison 1980). Since once accelerated CR hadrons can accumulate in galaxy clusters (Berezinsky et al. 1997) and produce a long-lived γ-flux signature (Miniati 2003; Pfrommer & Enßlin 2004; Ando & Nagai 2008; Donnert et al. 2010b; Pinzke & Pfrommer (2010)), observations in this energy range can provide an important test-bed for feedback models. Indeed, feedback episodes producing similar X-ray features at $z = 0$ might still contribute a different enrichment of CRs across a whole cluster lifetime, and therefore a different γ-flux from our simulated objects. In this section we investigate the level of secondary emission resulting from the acceleration of CRs in the different modes of AGN feedback.

In the two-fluid model used here, we cannot follow the spectral evolution of the CR population. Hence in order to compute the γ-ray flux from hadronic collisions we must assume a spectrum for...
the CRs at the time of observation. Shocks which developed in the already formed dense and hot ICM (z < 1) largely dominate the energy budget of shock acceleration in clusters, compared to earlier times (z > 1). It is therefore reasonable that the resulting population of CRs at later epochs has a spectral index that is associated with these Mach numbers. Using SPH simulations modelling the injection and energy evolution of CRs at cosmological shocks, Pinzke & Pfrommer (2010) recently derived an average $\alpha = 2.3$ injection spectrum for their sample of simulated clusters (for protons in the range of $\sim 1$–10 GeV). In our case, based on previous work with ENZO, we know that shocks that are mainly responsible for the injection of CRs for $z < 1$ are in the range of $2.5 \leq M \leq 3.5$ (e.g. Vazza et al. 2011b, and references therein), corresponding to a particle injection spectrum of $\alpha \sim 3.3$. This follows from the basic relation:

$$\alpha = 2 \cdot \frac{M^2 + 1}{M^2 - 1},$$

which applies to the case of non-radiative shocks.

In the following we will base our computation of the $\gamma$-flux on the limiting cases of $\alpha = 2.5$ ($M = 3$) and $\alpha = 3.3$ ($M = 2$).

Within the virial volume of clusters, the $\pi^0$ decay is expected to dominate the cluster emission above $> 0.1$ GeV with respect to other radiative mechanism (e.g. Inverse Compton of secondary electrons, non-thermal bremsstrahlung; Miniati 2003; Ando & Nagai 2008). We also neglect turbulent re-acceleration of CRs (e.g. Brunetti et al. 2007; Brunetti & Lazarian 2011a). Following the formalism of Pfrommer & Enßlin (2004) (see also Donnert et al. 2010b), we compute the emission from an asymptotic spectrum of particle, with a spectral index $\alpha_{\gamma} \approx \alpha$. The threshold proton energy is set to $E_{\text{min}} = 1$ GeV.

Our results for each implementation of AGN are shown in Fig. 12, where we show the absolute luminosity of simulated clusters in the [1–10] GeV energy range, (typically the most sensitive in terms of average differential energy flux) and the upper limits from Fermi observations of Ackermann et al. (2010), as a function of the total cluster mass within $R_{500} \approx R_{\text{vir}}/2$. The results in this energy range do not depend much on the assumed spectrum of particles, and the difference between $\alpha = 2.5$ and $\alpha = 3.3$ is only $\sim 30$ per cent in $\gamma$-flux (shown by different symbols).

All pure cooling runs produce an excess of $\gamma$-emission compared to Fermi upper limits, up to a factor of $\sim 10$. This is mainly due to the large density of thermal targets for the proton–proton collision within the cooling radius.

Runs with AGN feedback, on the other hand, are below present-day Fermi upper limits, with the exception of the quasar run of E5A, with $E_{\text{AGN}} = 10^{59}$ erg per event. The bubble feedback seems to provide the lowest amount of $\gamma$-emission across the sample, with $\gamma$-ray flux about $\sim 10$ times below the Fermi upper limits within each mass bin. Jet and quasar feedback also produce $\gamma$-emission below the upper limits, but by a smaller factor.

Based on current upper limits from Fermi (Ackermann et al. 2010) and the rather small sample of simulated clusters, it is not

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5 We note that in principle also the signal from DM annihilation can contribute to the same energy range [1–10] GeV (e.g. Pinzke, Pfrommer & Bergström 2011). However, this has not been observed yet (e.g. Ackermann et al. 2012), and the effect obviously strongly depends on the assumed cross-section of DM, a still open topic, and we do not model this contribution in any way. Indeed, our simulations can be helpful in assessing the statistical emission floor of $\gamma$-emission expected from structure formation processes and AGN feedback.
possible to reject any of the feedback models based on the predicted $\gamma$-ray luminosity. However, this approach can put robust constraints on feedback models and energetics, complementary to the analysis of X-ray profiles. Indeed, while the radial profiles of gas entropy, temperature and density studied in Section 3.1 cannot alone lead to a clear assessment of which feedback mode is more suitable to explain observations, a $\sim 5$–10 times lower limit on $\gamma$-emission could already rule out the jet/quasar modes.

Fujita & Ohira (2012) recently simulated the effects of injection, streaming and heating of CRs from the central AGN in the Perseus clusters, producing estimates of non-thermal radiation from secondary particles at several wavelengths. The $\gamma$-ray luminosities produced by our AGN runs for cluster H5 (which has a mass close to Perseus) are of the same order of magnitude as in the fiducial model in Fujita & Ohira (2012), $\sim 10^{41}$ erg s$^{-1}$. This is $\sim 2$ orders of magnitude below the Fermi upper limit at [1–10] GeV. Our AGN runs are similar to other cosmological simulations that estimate the $\gamma$-ray power from secondary particles in clusters (Donnert et al. 2010b; Pinzke & Pfrommer 2010), our results. Contrary to Pinzke & Pfrommer (2010), we do not excise dense overcooled clumps from the simulated volume and the contribution of shocks related to AGN activity is added to the contribution of CRs from cosmological shocks. While a part of the gas mass locked into these dense clump would eventually lead to star formation and produce cluster galaxies, these structures are the same that are responsible for the production of the unrealistic X-ray properties (Section 3.1) and therefore their excision would just ‘mask’ a dramatic problem of the simulation. In addition, without the inclusion of star formation processes in our simulation, it is difficult to establish which part of these cold clumps would turn into galaxies, and therefore removing their contribution in $\gamma$-emission would be arbitrary. The $\gamma$-ray power from the CRs accelerated at cosmological shocks only is slightly smaller than in Pinzke & Pfrommer (2010). The fact that the total $\gamma$-ray power from our clusters is lower than in SPH calculations stems from the typically lower innermost gas density resulting in Eulerian simulations, and also in the different way in which SPH and grid methods model the accretion of gas matter within cluster cores, as already investigated in Vazza et al. (2011b). For the numerical reasons for that, we refer the reader to Agertz et al. (2007), Wadsley, Veeravalli & Couchman (2008) and Mitchell et al. (2009).

### 3.4 Turbulent motions

Feedback from AGN may add turbulent energy to the already turbulent state of the ICM. Unlike in our previous work (Vazza, Roediger & Brueggen 2012b), with this set of simulations we can study turbulent motions from, both the accretion of matter and AGN feedback (in its different modes).

In Fig. 13, we show a map of turbulence reconstructed with the same multiscale filtering technique of Vazza et al. (2012b), considering one run with jet feedback (top panels) and in one with quasar feedback (bottom panels). From left to right, the maps of gas density, total velocity and turbulent for a thin slice (25 kpc $h^{-1}$)

![Figure 13](https://example.com/figure13.png)
through the cluster centre are shown. This system has an ongoing merger at this redshift, plus large-scale accretion of gas/DM matter along at least three filaments. These processes drive motions with bulk velocities of \(\sim 1500-2000 \text{ km s}^{-1}\) on \(\sim \text{Mpc}\) scales, and turbulent velocities of \(\sim 600-800 \text{ km s}^{-1}\) on scales of \(\sim 300 \text{ kpc}\). In the run with jets an additional horizontal velocity pattern of \(\sim 600-700 \text{ km s}^{-1}\) is present (indicated by an arrow within the panels). This is the outcome of a recent jet burst, launched \(\sim 0.1 \text{ Gyr}\) ago. Even if the jet output dominates the velocity and the turbulent velocity field in the surroundings of the cluster core \(< 100-200 \text{ kpc}\), making it anisotropic, the overall velocity and turbulence within the cluster volume are dominated by the large merger, with a pattern similar to the quasar mode.

In general, we find that feedback affects the turbulent velocity field in our simulations in two ways. First, by driving turbulence locally to the AGN (e.g. along the jets or behind the wake of bubbles), in addition to the overall cluster velocity field. This is a general finding in simulations (e.g. Scannapieco & Brüggen 2008; Heinz, Brüggen & Morsony 2010; Dubois et al. 2011; Gaspari et al. 2011b). Secondly, by affecting the compactness of accreted substructures and cluster satellites, thus affecting their ram-pressure-stripping and their efficiency in stirring the ICM. Overall, this makes the trend of turbulence in the different feedback modes non-trivial to identify, and close to the AGN highly time dependent.

This is confirmed also by the radial profiles of velocity and turbulence for the three most massive clusters (Fig. 14). While the velocity profiles at \(z = 0\) are quite similar (except that for the cluster core) in E1, increasingly larger variations between modes are found in E5A and in H5. In all cases, the pure cooling run produces the highest total and turbulent velocity field. This is typical of pure cooling runs (e.g. Dubois et al. 2011; Li & Bryan 2012), and a result of the transonic cooling flow. In addition, overcooling leads to more compact substructures that are more efficient drivers of turbulent motions during their orbits (e.g. Valdarnini 2011).

Sanders, Fabian & Smith (2011) recently computed upper limits from the maximally allowed amount of turbulence for a collection of 28 nearby (mostly cool-core) galaxy clusters, by fitting a thermal multitemperature spectrum to observed \(\textit{XMM–Newton}\) spectra. Following the same procedure as in Vazza et al. (2011a), we computed the turbulent velocity field on \(\sim 30 \text{ kpc}\) scales (which roughly corresponds to the projected volume available to the observations of Sanders et al. 2011) for our cluster runs. Since the turbulent energy spectrum on the smallest spatial scales may be affected by numerical effects on the smallest scale (e.g. Porter & Woodward 1994), the energy of the turbulent motions on scales \(\leq 30 \text{ kpc}\) was calculated analytically from the measured total power spectrum on larger scales assuming Kolmogorov scaling.\(^6\)

In Fig. 15 we show the comparison between the simulated points at \(z = 0\) and the \(\textit{XMM–Newton}\) limits for the galaxy clusters of the sample. As in Vazza et al. (2011a), the values for the cores of simulated clusters are generally below the observed upper limits. However, the pure cooling runs show a velocity slightly in excess of some observed objects.

AGN feedback generally reduces turbulent velocities within the core (as shown above) and pushes the observed temperature from the core to higher values. Basically all observable turbulent velocities on

\(^6\) In this case the Kolmogorov slope maximizes the possible contribution of unresolved structures of the velocity field, since in general a slightly steeper power spectrum is measured in these simulations at the smallest scale (Vazza et al. 2009a, 2011a). Numerical dissipation makes it difficult to constrain the slope at the smallest scale with precision, and therefore our choice here already provides the most robust possible test against observed upper limits of turbulence.
Figure 16. Simulated Doppler broadening of Fe XXIII line along three projection of cluster E1 (top) and E5A (bottom) at $z = 0$. Both thermal and velocity broadening and considered. The emission is extracted from a projected area of $0.1 \times 0.1 \text{ Mpc}^{-2}$. In each model the emission is normalized to the total inside the area.

the $\sim 30$ kpc scale are below upper limits\(^7\) (with the exception of the resimulation of E5A using bubbles, in which the turbulent velocity is of the order of the 2 lowest available upper limits within the same temperature range). This statistics is much more time dependent than the $\gamma$-ray fluxes, given the very small time-scale associated with a change of the average innermost temperature and small-scale gas velocity, in response to AGN feedback events. In these runs, we verified that variations of factors of $\sim 2$--5 in the average temperature, and of factors of $\sim 2$--3 in small-scale turbulence, can easily be found by comparing epochs separated by $\sim 100$ Myr. Radiative cooling and dissipation of turbulent motions on one hand, and violent heating and driving of outflows from the AGN on the other hand can cause such negative and positive fluctuations of the measured temperatures and velocities inside $\sim 30$ kpc. Taking this into account, we suggest that by using this technique it may be less straightforward to unveil the presence of specific AGN modes in the real observation. Nevertheless, this approach appears still useful to limit the available energy budget of AGN feedback.

A complementary viable option in the near future is represented by X-ray spectroscopy of Doppler-broadened iron lines in the ICM, such as the Fe XXIII line at $\sim 6.7$ keV. Several theoretical works already tested the impact of mergers (e.g. Sunyaev, Norman & Bryan 2003; Brüggen, Hoeft & Ruszkowski 2005; Dolag et al. 2005; Vazza, Gheller & Brunetti 2010b; Zhuravleva et al. 2012) or AGN feedback (e.g. Brüggen et al. 2005; Heinz et al. 2010) in shaping the Fe XXIII line with numerical simulations. In this case we can provide an overall view of the impact of various AGN modes on the shape of the Fe XXIII line in our simulated clusters.

In Fig. 16, we show the simulated broadening of the iron line from a region of $100 \times 100 \text{kpc}^2$ centred on clusters E1 and E5A, considering the three lines of sights. We also included the effect of thermal broadening since feedback can simultaneously change the temperature of emitting gas along the line of sight. To normalize the effect of very bright emission in the cooling run, we normalize all lines to their integrated luminosity within the field of view. The general effect of AGN feedback is to broaden the emission line, compared to the pure cooling run, producing additional structures of high-velocity tails (even if with very low associated luminosity) with a full width at half-maximum (FWHM) $\sim 20$--30 eV. The different feedback modes present the largest difference along the $z$-direction (which is the direction of the jets). Run E1 presents the largest difference, since jets were active more recently in this system. However, we find that in general disentangling the role of gravity-induced motions and of non-gravitational processes is a very difficult task. Another problem is that the high-velocity material must entrain enough high-emissivity material to be detectable (Brüggen et al. 2005; Heinz et al. 2010). In order to efficiently deal with ‘width-driven’ or ‘separation-driven’ features of the broadened emission, and to disentangle the different sources of them, sophisticated techniques are being developed (e.g. Shang & Oh 2012, and references therein).

\(^7\) Recently, Bulbul et al. 2012 derived an upper limit of $\sim 200$ km/s for the centre of cooling flow cluster A3112, which is also above the values we find here.
4 DISCUSSION

In this work we simulated the evolution of thermal and non-thermal properties of a small sample of galaxy clusters with a customized version of the AMR code ENZO (Norman et al. 2007; Collins et al. 2010). The basic features of our two-fluid model have been presented in Vazza et al. (2012a), while the implementation of shock re-acceleration of CRs, Coulomb and secondary losses and different modes of AGN feedback have been introduced in this work (Sections 2.1 and 2.2). To our knowledge, this is the first time that non-thermal effects connected to cosmological shock waves and AGN feedback are studied with cosmological simulations. We tested the performance of a subset of recipes for AGN feedback (see, however, Appendix A for a larger survey of models) against available observations of thermal profiles derived from Chandra X-ray observations (Section 3.1), upper limits of secondary $\gamma$-emission from Fermi observations (Section 3.3) and upper limits of turbulent motions from XMM–Newton observations (Section 3.4). Our main result is that non-thermal observables allow us to assess the reliability of each feedback mode against available upper limits, and is thus complementary to X-ray observations. For a more detailed discussion of the possible consequences of this method we refer the reader to Section 5.

Here we list the main limitations of our current numerical method, and the way in which our results can be affected or biased.

First, our recipe to identify AGN-like cells in the simulated cluster volume (Section 2.2) relies on the heuristic choice of a threshold in gas density ($n_{\text{th}} = 10^{-2}$ cm$^{-3}$). This choice is based on a comparison with the typical gas density of environments hosting supermassive BHs, reported in numerical work by other groups (e.g. Sijacki et al. 2007; Teyssier et al. 2011). The lack of the more consistent use of sink particles to model at run-time the growth and accretion rate of BHs can be addressed with future developments in ENZO 2.0 (Collins et al. 2010).

Secondly, we re-simulated a few clusters with several implementations of AGN feedback in order to compute the final budget of CR energy and their related $\gamma$-flux. These simulations are fairly expensive, and an extended survey of a large sample of clusters resimulated with all variations of AGN feedback is currently beyond our means. For this reason, an investigation of the presence of a bimodality in the distribution of cool-core and non-cool-core clusters in our data set was not possible. This is left to future work.

The recipe for radiative cooling is fairly idealized, and relies on the public implementation of equilibrium cooling in a fully ionized H–He plasma with constant metallicity. Even though a more self-consistent inclusion of metal ejection from supernovae and galactic winds and line cooling can exacerbate the cooling catastrophe in radiative simulations (Dubois et al. 2011), the overall energy budget required from AGN feedback in our simulations (and its influence on the CR-energy budget) should not be significantly affected. However, the inclusion of metals in our description of the ICM can provide an additional way of studying turbulent motions from the AMR region) is sufficient to capture shock waves and turbulent features related to cluster mergers (as in Vazza et al. 2011a). However, it is barely enough to capture the interplay between the AGN region and the cluster core. Modelling the accretion rate on the central galaxy at the centre of the cooling radius (Li & Bryan 2012), the small-scale interaction between jets (e.g. Heinz et al. 2006; Morsony et al. 2010; Gaspari, Ruszkowski & Sharma 2012) or inflated bubbles (e.g. Scannapieco & Brüggen 2008; Sijacki et al. 2008) requires a resolution of the order of $<$kpc. Moreover, to resolve the turbulence excited by cluster mergers, sloshing and AGN jets in the same simulation, one would need to cover scales ranging from $R_{\text{vir}} \sim 3$ Mpc down to the presumed scale of physical dissipation at $\sim$0.1 kpc, in a rather uniform way, for a range of scales of $10^2$–$10^4$.

5 CONCLUSIONS

What can be learned from this exercise of comparing thermal and non-thermal observables of simulated and observed clusters? We argue that the approach outlined here can put robust constraints on the energetics, duty cycle, mechanism and epochs of feedback from AGN. Even if with present data it is not yet possible to reject specific implementations of feedback, it can be a powerful approach in the near future. The amount of CR injection after each AGN burst is assumed to be given by the shock acceleration efficiency of difusive shock acceleration in Kang & Jones (2007) and Caprioli (2012). The other mechanisms of dynamical (e.g. advection with the fluid) or energy (e.g. secondary losses) evolution of CRs depend the dynamics of the simulated ICM. All additional mechanisms of CR injection that we neglected here (e.g. direct injection from supernovae, galactic winds, magnetic reconnection) cannot but increase the budget of CRs in the ICM, even if not substantially. Therefore, it is likely that our limits of $\gamma$-emission from CRs are slightly low. We also remark that other mechanisms of CRs, such has CRs diffusion (e.g. Hanasz & Lesch 2000; Jubelgas et al. 2008), should be negligible for the $>25$ kpc $h^{-1}$ scales of interest here (e.g. Blasi, Gabici & Brunetti 2007, and references therein).8

Therefore, in the near future a set of $\gamma$-observation significantly below these numerical estimates for jets/AGN feedback may imply one of the following possibilities.

(i) The real power per event for each AGN burst is substantially lower than what we assumed here ($\sim 10^{44}$–$10^{45}$ erg s$^{-1}$) with a

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8 In Enßlin et al. (2011) it is argued that if CR can stream along a quasi-radial magnetic field much faster than the Alfven speed, the CR-energy density in radio-quiet clusters would be greatly reduced. However, it seems that such an hypothesis can be excluded on theoretical grounds (Achterberg 1981; Schlickeiser 1989, 1994; Farmer & Goldreich 2004), and also based on a large number of Faraday Rotation (Enßlin & Vogt 2003; Clarke 2004; Murgia et al. 2004; Guidetti et al. 2008; Bonafede et al. 2010; Vacca et al. 2010) and polarization (Bonafede et al. 2011) data from nearby clusters that seem to exclude a systematic difference in the topology of the ICM magnetic fields between clusters with and without large-scale emission.
different duty cycle. However, such large powers have been inferred from observations in several cases (e.g. McNamara & Nulsen 2007; Stott et al. 2012, and references therein).

(ii) The acceleration efficiency of CRs at $M < 10$ shocks (which are typical in AGN bursts and cluster mergers) is lower than what we assumed here. Indeed, the details of particle acceleration for $2 < M < 10$ are not yet robustly constrained by theory due to the difficulty of modelling the large range of spatial and temporal scales involved in the diffusive acceleration at such shocks (e.g. Kang & Ryu 2010). More recently, several groups employing particle-in-cells methods investigated additional acceleration mechanisms for particles at shocks (e.g. shock-drift acceleration), suggesting the possibilities of a different dependence on Mach number (Gargaté & Spitkovsky 2012). In addition, there is now growing evidence that the non-linear diffusive shock acceleration model has to be slightly revised to fully explain recent data from supernovae (Caprioli 2012).

(iii) The actual quenching of catastrophic cooling in real clusters can happen over time through a mixture of ‘violent’ (jets, quasar) and more ‘quiet’ (e.g. bubbles) episodes. A physically motivated mixture of these different violent and quiet phases may in principle quench the cooling catastrophe without injecting too large CR energy in the ICM. Theoretical work, indeed, suggests that this is a viable possibility (e.g. Sijacki et al. 2007; McCarthy et al. 2008; Short et al. 2012).

Based on the results presented in this paper, we argue that in the future a careful modelling of non-thermal observables will be important to improve our understanding of AGN feedback. Despite the energy that is theoretically available for AGN feedback, the AGN cannot be arbitrarily impulsive or continuous because in both cases this will affect observable non-thermal phenomena (such as turbulence and the injection of CR energy). In particular, given the extremely long time for Coulomb and hadronic losses of CR protons in the ICM, the investigation of (lack of) $\gamma$-emission or radio emission from secondary particles is a powerful tool to unravel feedback during the earliest phases of structure formation.

ACKNOWLEDGMENTS

We thank the referee for the very helpful comments, which improved the final quality of the paper. FV and MB acknowledge support from the grant FOR1254 from the Deutsche Forschungsgemeinschaft. FV acknowledges the usage of computational resources under the CINECA-INAF 2008-2010 agreement, and at the John-Neumann Institut at the Forschungszentrum Jülich. We thank J. Donnert, D. Collins, M. Gaspari, F. Brighenti & K. Dolag and G. Brunetti for very useful scientific discussions, and J. Sanders for kindly providing the observed data points of Fig. 15. We gratefully acknowledge the ENZO development group for providing extremely helpful and well-maintained online documentation and tutorials (http://lca.ucsd.edu/software/enzo/).

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APPENDIX A: TESTS WITH VARYING PARAMETERS

In this appendix we show results of a more extended study of the variation of thermal and CR properties of one cluster run (H10), with a more systematic exploration of the parameter space of our implementation of AGN feedback. To save computational time, all tests in this case have been performed using the standard mesh refinement strategy, where the grid is refined in regions where the gas/DM overdensity is larger than three times the overdensity of the parent cell (the differences in the thermal properties inside $R_{200}$ are very small compared to the AMR criteria used in the main article, while in general the properties of accretion shocks and turbulent motions tend to be significantly affected by resolution issues and numerical dissipation, as discussed in Vazza et al. 2009a and Vazza 2011).

Fig. A1 shows the projected gas density and a temperature cut for four resimulations of this cluster for the pure cooling case ($C$) and for three feedback models with similar feedback energy budget ($A2$, $K2$ and $B2$). Despite the fact that the outer accretion shocks are poorly described because of the AMR strategy employed here, the innermost region where the AGN feedback plays a role is resolved similar to the runs studied in the main article.

Table A1 lists all resimulations of H10 performed, with details on the adopted feedback model. In the ensemble of profiles shown in Figs A2–A4 we show all profiles of thermal and CRs related properties for all resimulations.

We compared one standard non-radiative run with CR feedback only from cosmological shock acceleration (as in Vazza et al. 2012a, run NR0), one run where also the Coulomb and secondary

| ID  | Cooling | Feedback mode | Mnemonic          |
|-----|---------|---------------|-------------------|
| NR0 | No      | No            | No cooling, no. CR losses |
| NR1 | No      | No            | No cooling, CR losses |
| C   | Yes     | No            | Cooling           |
| A1  | Yes     | Thermal, $T_{\text{AGN}} = 10^7$ K | Quasar low |
| A2  | Yes     | Thermal, $T_{\text{AGN}} = 10^8$ K | Quasar med. |
| A3  | Yes     | Thermal, $T_{\text{AGN}} = 10^9$ K | Quasar high |
| A0  | Yes     | Thermal, $T_{\text{AGN}} = 10^9$ K $z \geq 1$ | Early quasar |
| K2  | Yes     | Kinetic, $v_{\text{jet}} = 10^3$ km s$^{-1}$ | Jets high |
| K4  | Yes     | Kinetic, $v_{\text{jet}} = 10^2$ km s$^{-1}$ | Jets low |
| B2  | Yes     | Buoyant, $\delta_{\text{bl}} = 0.1$ | Bubbles |
| B4  | Yes     | Buoyant, $\delta_{\text{bl}} = 0.05$ | Bubbles |
| BC  | Yes     | Buoyant, $\delta_{\text{bl}} = 0.05, \phi_{\text{cr}} = 10$ | Bubbles |

losses are modelled ($NR1$) and the pure cooling case with losses for CRs ($C$).

Some results can be derived from this preliminary comparison of feedback modes, in addition to those already discussed in the main article. (a) The adoption of a more standard AMR criterion still gives internal profiles and trends with AGN feedback very similar to the more expensive resimulations with AMR based also on velocity jumps. (b) The thermal properties of the cluster are unchanged by the adoption of CR losses at run time (Fig. A2). The amount of CR energy within the innermost 100 kpc and the production rate of secondary particles (equation 1) are however reduced by a factor...
Figure A2. Radial profiles of gas entropy, gas density, gas temperature, pressure ratio $P_{cr}/P_g$, baryon fraction and secondary injection for the resimulations of cluster H10 employing radiative cooling only, and non-radiative physics with and without CR losses. We additionally show as grey line the profile of the clusters in the sample of Cavagnolo et al. (2009).

Figure A3. Same as in Fig. A2, but for resimulations of H10 with different implementations of thermal feedback from quasars.

of $\sim 10$ due to CR losses. However, the inclusion of CR losses is expected to reduce the cooling rate in radiative simulations, owing to the larger gas density attained there. However, CR losses are not able to stem the cooling flow, unless other heating mechanisms by CRs (e.g. heating from Alfvén waves excited by the streaming of CRs in a $\sim 1–10$ µG magnetic field; Fujita & Ohira 2011) are at work. (c) In the case of quasar feedback, an energy per event of $10^{60}$ erg (i.e. 10 times larger than the fiducial model for H10 discussed in the main
paper) in a cluster of this mass creates a baryon poor system, and
an unrealistically large ratio of CR to gas energy (∼40 per cent within
the virial radius). (d) For the quasar mode (Fig. A3), an energy
per event of $10^{58}$ erg (i.e. 10 times smaller than the fiducial model
for H10 discussed in the main paper) can produce an acceptable
match to the observed X-ray profiles, similar to what we reported
for the two largest cluster masses (Section 3.1). If AGN feedback
is switched off too early ($z = 1$), a cooling catastrophe develops
only for a small region, $\leq 50$ kpc. (e) In the jet mode (Fig. A4), too
slow jets ($\leq 10^2$ km s$^{-1}$) are unable to quench the cooling flow. (f)
At this rather poor resolution, the investigated differences in the
initial density contrast of bubbles (Fig. A4) or in their initial energy
composition (i.e. thermal energy or CR-energy dominated) produce
extremely similar result on the thermal and CR properties of the
cluster at $z = 0$.

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