Mass distribution in galaxy clusters: the role of Active Galactic Nuclei feedback

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Abstract: We use 1-kpc resolution cosmological Adaptive Mesh Refinement (AMR) simulations of a Virgo-like galaxy cluster to investigate the effect of feedback from supermassive black holes on the mass distribution of dark matter, gas and stars. We compared three different models: (i) a standard galaxy formation model featuring gas cooling, star formation and supernovae feedback, (ii) a ‘quenching’ model for which star formation is artificially suppressed in massive haloes and finally (iii) the recently proposed active galactic nucleus (AGN) feedback model of Booth and Schaye. Without AGN feedback (even in the quenching case), our simulated cluster suffers from a strong overcooling problem, with a stellar mass fraction significantly above observed values in M87. The baryon distribution is highly concentrated, resulting in a strong adiabatic contraction (AC) of dark matter. With AGN feedback, on the contrary, the stellar mass in the brightest cluster galaxy (BCG) lies below observational estimates and the overcooling problem disappears. The stellar mass of the BCG is seen to increase with increasing mass resolution, suggesting that our stellar masses converge to the correct value from below. The gas and total mass distributions are in better agreement with observations. We also find a slight deficit (~10 per cent) of baryons at the virial radius, due to the combined effect of AGN-driven convective motions in the inner parts and shock waves in the outer regions, pushing gas to Mpc scales and beyond. This baryon deficit results in a slight adiabatic expansion of the dark matter distribution that can be explained quantitatively by AC theory.

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Mass Distribution in Galaxy Clusters: the Role of AGN Feedback

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ABSTRACT

We use 1 kpc resolution cosmological AMR simulations of a Virgo–like galaxy cluster to investigate the effect of feedback from supermassive black holes (SMBH) on the mass distribution of dark matter, gas and stars. We compared three different models: (i) a standard galaxy formation model featuring gas cooling, star formation and supernovae feedback, (ii) a “quenching” model for which star formation is artificially suppressed in massive halos and finally (iii) the recently proposed AGN feedback model of Booth & Schaye (2009). Without AGN feedback (even in the quenching case), our simulated cluster suffers from a strong overcooling problem, with a stellar mass fraction significantly above observed values in M87. The baryon distribution is highly concentrated, resulting in a strong adiabatic contraction (AC) of dark matter. With AGN feedback, on the contrary, the stellar mass in the bright central galaxy (BCG) lies below observational estimates and the overcooling problem disappears. The stellar mass of the BCG is seen to increase with increasing mass resolution, suggesting that our stellar masses converge to the correct value from below. The gas and total mass distributions are in striking agreement with observations. We also find a slight deficit (∼10%) of baryons at the virial radius, due to the effect of AGN-driven shock waves pushing gas to Mpc scales and beyond. This baryon deficit results in a slight adiabatic expansion of the dark matter distribution, that can be explained quantitatively by AC theory.

Key words: black hole physics – cosmology: theory, large-scale structure of Universe – galaxies: formation, clusters: general – methods: numerical

1 INTRODUCTION

Galaxy clusters are ideal laboratories to study galaxy formation in a dense environment. Galaxies in clusters are observed in many morphological types, from blue extended spirals to red massive elliptical spheroids. The origin of the morphological evolution of galaxies in clusters is still poorly understood. Tidal and ram pressure stripping trigger fast evolution in the properties of accreted satellites, while complex gas cooling and heating processes control the amount of stripped gas that can actually reach the central region of the cluster. In this context, the origin of bright cluster galaxies (BCG) still raises many questions. In the current cosmological framework, the formation of galaxies at the bright end of the luminosity function is still affected by the so–called ”overcooling problem”: using both semi-analytical models and computer simulations, it has been shown that the massive galaxies are predicted to be too bright and too blue when compared to massive galaxies in the nearby universe (see the recent review by Borgani & Kravtsov (2009)). As a consequence, these models find a stellar content in massive clusters that is significantly above the observed values (Kravtsov et al. 2003), even including rather extreme supernovae feedback recipes (Borgani et al. 2004).

In order to overcome this issue, feedback from supermassive black holes (SMBH) have been proposed as a mechanism to prevent gas from accumulating in the cluster core. The so–called AGN feedback scenario has received support from theoretical considerations (Tabor & Binney 1993; Ciotti & Ostriker 1997; Silk & Rees 1998), but the strongest evidence comes from the correlated observations of X-ray cavities and radio blobs in massive clusters. These

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features are usually interpreted as buoyantly rising bubbles of high entropy material injected in the cluster core by jets of relativistic particles. Although detailed models of jets have been proposed in the context of cluster cores heating (Churazov et al. 2001; Reynolds et al. 2001; Omma et al. 2004; Ruszkowski et al. 2004; Brüggen et al. 2005; Cattaneo & Teyssier 2007), they are beyond the scope of present day cosmological simulations. Based on simple energetic arguments, it is however possible to relate the growth of SMBHs at the centre of massive galaxy spheroids to the energy required to unbind the cooling gas (Silk & Rees 1998). The idea of star formation being regulated by AGN feedback at the high mass end of the galaxy mass function has been applied first quite successfully to hydrodynamical simulations of galaxy merger (Matteo et al. 2003) and then to semi-analytical models of galaxy formation (Bower et al. 2006; Cattaneo et al. 2006; Lucia & Blaizot 2007; Cattaneo et al. 2009).

AGN feedback models have been included only recently in cosmological simulations of galaxy groups and clusters (Puchwein et al. 2008; McCarthy et al. 2009). Although the detailed physical modeling of SMBHs growth usually differs (Sijacki et al. 2007; Booth & Schaye 2009), these simulations, exclusively based on the GADGET code (Springel 2005), have obtained very encouraging results regarding the global properties of the simulated clusters (Puchwein et al. 2008; McCarthy et al. 2009; Puchwein et al. 2010). In this paper, we report on the first AMR high-resolution simulation of a Virgo-like cluster, following both SMBH and star formation, with the associated feedback. We use the AMR code RAMSES, which differs significantly from the other code used so far to model AGN feedback in a fully cosmological simulation, namely the GADGET code. There are some definitive advantages to using AMR in this context: it is strictly energetic, meaning that it is very important in presence of strong shocks, and it captures hydrodynamical instabilities more realistically (Agertz et al. 2007; Wadsley et al. 2008; Mitchell et al. 2009), which is very important in presence of convective motions of buoyant gas and it captures the hydrodynamical gas stripping of infalling satellites.

We have adapted the SMBH growth model of Booth & Schaye (2009) to the sink particle method for AMR presented by Krumholz et al. (2004). With respect to the previous work of Booth & Schaye (2009) and follow-up papers, we have made significant improvements over the OWL simulations suites in term of mass and spatial resolution, but only for one single zoom-in simulation of a Virgo-like cluster. Recently, Puchwein et al. (2008) and Puchwein et al. (2010) have also used the GADGET code, but a different AGN feedback model, to perform zoom-in simulations of groups and clusters of galaxies, with however a mass and spatial resolution not as good as the ones we used here. In this paper, we have specifically chosen a Virgo-like cluster, in order to compare our results with the very detailed observations that are available for this well-known astronomical object. We will focus here on the mass distribution of the three main components, namely dark matter, gas and stars.

The paper is organized as follows: the first section is dedicated to numerical methods and physical ingredient (cooling, star formation and AGN feedback), while our second section presents our results, comparing our three models. The final section is left for discussion.

2 NUMERICAL METHODS

In this section, we describe the numerical techniques and the initial conditions we used to model our Virgo-like cluster. As it is now customary for cosmological simulations, we used a zoom-in (or volume renormalisation) technique to focus our computational resources on a specific region of a 100 Mpc/h periodic box. We adopt a standard ΛCDM cosmology with Ω_m = 0.3, Ω_Λ = 0.7, Ω_b = 0.045 and H_0 = 70 km/s/Mpc. We have adopted the Eisenstein & Hu (1998) transfer function and the grafic package (Bertschinger 2001) in its parallel implementation mpgrafic (Prunet et al. 2008) to generate our initial conditions. From a first low resolution dark matter only run, we built a catalog of candidate halos whose virial masses lie in the range 10^{14} to 2 × 10^{14} M⊙/h. From this catalog, we have extracted our final halo based on its mass assembly history: its final mass (M_{vir} ≃ 10^{14} M⊙) is already in place around z = 1, so it can be considered as a well relaxed cluster by z = 0.

2.1 Simulation parameters

We have performed two simulations, one at low resolution, for which the initial grid effective size was 1024^3, and one at high resolution, with effective grid size of 2048^3. From this initial grid, we have extracted our final halo based on its mass assembly history, so that the total number of particles in the box was 5.2 × 10^8 (resp. 22 × 10^6) for only 2.6 × 10^6 (resp. 19 × 10^6) in the central region, and 10^8 (resp. 8 × 10^6) inside the virial radius for the low resolution (resp. high resolution) simulation. The dark matter particle mass is therefore 6.5 × 10^5 (resp. 8.2 × 10^6) M⊙/h and the baryons resolution element mass is 1.2 × 10^7 (resp. 1.4 × 10^8) M⊙/h.

The AMR grid was initially refined to the same level of refinement of the particle grid (1024^3 and 2048^3), and 7 more levels of refinements were considered. We imposed the spatial resolution to remain roughly constant in physical units, so that the minimum grid cell stayed closed to Δx_{min} = L/2^t_{max} with t_{max} = 17 (resp. 18) at z = 0. We therefore reached a spatial resolution of Δx_{min} ≃ 1 kpc for the low resolution simulation and Δx_{min} ≃ 500 pc for the high resolution one. The grid was dynamically refined up to this resolution using a quasi-Lagrangian strategy: when the dark matter or baryons mass in a cell reaches 8 times the initial mass resolution, it is split into 8 children cells. We reached z = 0 with 14 × 10^6 (resp. 68 × 10^6) cells for the low (resp. high) resolution run, including split cells.

Gas dynamics is modeled using a second-order unsplit Godunov scheme (Teyssier 2002; Teyssier et al. 2006; Fromang et al. 2006) based on the HLLC Riemann solver (Toro et al. 1994). We assume a perfect gas equation of state (EOS) with γ = 5/3. Gas metallicity is advected as a passive scalar, and is self-consistently accounted for in the cooling function. We also considered the standard homogeneous UV background of Haardt & Madau (1996), but we modified the starting redshift, extrapolating the average intensity...
from $z_{\text{Reion}} = 6$ to $z_{\text{Reion}} = 12$, in order to account for the early reionization expected in such a proto-cluster regions (Iliev et al. 2008).

### 2.2 Galaxy formation physics

As gas cools down and settles into centrifugally supported discs, we need to provide a realistic model for the interstellar medium (ISM). Since the ISM is inherently multiphase and highly turbulent, it is beyond the scope of present-day cosmological simulations to try to simulate it self-consistently. It is customary to rely on subgrid models, providing an effective EOS that capture the basic turbulent and thermal properties of this gas. Models with various degrees of complexity have been proposed in the literature (Yepes et al. 1997; Springel & Hernquist 2003; Schaye & Vecchia 2008). We follow the simple approach based on a temperature floor given by a polytropic EOS for gas

$$T_{\text{floor}} = T_\ast \left( \frac{n_{\text{H}}}{n_\ast} \right)^{\Gamma^{-1}}$$

where $n_\ast = 0.1 \, \text{H/cc}$ is the density threshold that defines the star forming gas, $T_\ast = 10^4 \, \text{K}$ is a typical temperature mimicking both thermal and turbulent motions in the ISM and $\Gamma = 5/3$ is the polytropic index controlling the stiffness of the EOS. Gas is able to heat above this floor, but cannot cool down below it. Note that because of this temperature floor, the Jeans length in our galactic disc is always resolved. We also consider star formation using a similar phenomenological approach. In each cell with gas density larger than $n_\ast$, we spawn new star particles at a rate given by

$$\rho_\ast = \epsilon_\ast \frac{\rho_{\text{gas}}}{t_H} \quad \text{with} \quad t_H = \sqrt{\frac{3\pi}{2G\rho}}$$

where $t_H$ is the free-fall time of the gaseous component and $\epsilon_\ast = 0.01$ is the star formation efficiency. The star particle mass depends on the resolution and was chosen to be $2.4 \times 10^6$ (resp. $3 \times 10^5$) $M_\odot$ for the low (resp. high) resolution runs. For each star particle, we assume that 10% of its mass will go supernova after 10 Myr. We consider a supernova energy $E_{\text{SN}}$ for each star particle, and spatial resolution (in physical units) for our 2 sets of simulations.

<table>
<thead>
<tr>
<th>Run</th>
<th>$m_{\text{cdm}}$</th>
<th>$m_{\text{bar}}$</th>
<th>$m_\ast$</th>
<th>$\Delta x_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low res</td>
<td>65</td>
<td>12</td>
<td>2.4</td>
<td>0.76</td>
</tr>
<tr>
<td>High res</td>
<td>8.2</td>
<td>1.4</td>
<td>0.3</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table 1. Mass resolution for dark matter particles, gas cells and star particles, and spatial resolution (in physical units) for our 2 sets of simulations.

For each star particle, we assume that 10% of its mass will be ejected as metals per 10 $M_\odot$ average progenitor mass. This supernovae feedback was implemented in the RAMSES code using the "delayed cooling" scheme (Stinson et al. 2006).

Up to this point, we use rather standard galaxy formation recipe, which have proven only recently to be quite successful in reproducing the properties of field spirals (Mayer et al. 2008; Governato et al. 2009, 2010). The same recipe are only marginally successful when one considers small groups (Feldmann et al. 2010), but they fail on cluster scales (Borgani et al. 2004; Kravtsov et al. 2003; Borgani & Kravtsov 2009). In the present paper, in order to check that our results are compatible with previous work, and to set a reference point, we have performed simulations with only standard galaxy formation physics (labelled SF runs in the followings).

### 2.3 Star formation quenching

The main problem we have to face in standard cosmological simulations on cluster scales is the striking excess of mass locked into stars. Using rather extreme stellar feedback models, previous authors report that the simulated stellar mass fraction lies in the range 35 – 60%, depending on the cluster mass (Borgani & Kravtsov 2009). Since only 10% of the baryonic mass is observed in the galaxies, this would require a large amount of stars hidden in a diffuse component such as the intracluster light (ICL). This last scenario is however severely constrained by observations of the ICL (Gonzalez et al. 2007) and does not appear to be plausible.

There is growing theoretical and observational evidence that star formation is shutdown above a critical halo mass $M_h \approx 6 \times 10^{11} \, M_\odot$ (Cattaneo et al. 2006; Birnboim & Dekel 2003) have proposed that this critical mass is related to the stability of accretion shocks, and to a transition from cold to hot mode of gas accretion. Although this transition in the nature of the accretion flows has been confirmed by numerical simulations (Keres et al. 2005; Ocvirk et al. 2003; Dekel et al. 2006), the simulated star formation was not observed to decrease significantly above the critical mass (Ocvirk et al. 2008). This might be due to insufficient mass and spatial resolution, so that heating processes, not properly captured, cannot balance radiative cooling (Naab et al. 2005). On a different side, Cattaneo et al. (2006) argued that this modification of the halo properties may create favorable conditions for AGN feedback to be effective, but AGN feedback is still needed to prevent the overcooling problem above the critical mass (Dekel & Birnboim 2006).

Without specifying the underlying heating process, the critical mass argument boils down to stopping (or quenching) gas cooling and star formation in the central galaxy for halo masses larger than $\sim 10^{12} \, M_\odot$.

In this paper, in order to test this hypothesis, we have used a simple phenomenological model to quench star formation in massive galaxies. Since our standard model (SF runs) obviously suffers from a strong overcooling problem, we need to actively suppress gas cooling and star formation above the critical mass. If the stellar mass density is greater than $0.1 \, \text{H/cc}$, and if the stellar velocity dispersion is greater than 100 km/s, we switch off star formation and gas cooling. In this way, star formation in discs is unaffected, since the velocity dispersion is smaller than the chosen threshold. On the other hand, star formation is suppressed in massive spheroids. The main advantage of this quenching model is its simplicity: although it captures the scenario proposed by Cattaneo et al. (2006), it does not require any complex AGN feedback model, nor the mass and spatial resolution reached by Naab et al. (2007) in their early–type galaxy simulation. However, as we demonstrate in this paper, this simple approach doesn’t solve the overcooling problem in our Virgo cluster simulation.
2.4 SMBH growth and associated feedback

Beside our standard galaxy formation and our quenching scenario simulations, we explore a model for which SMBH growth and feedback is considered. In a nut shell, our recipe is based on the sink particle method for grid-based codes designed by Krumholz et al. (2004), with the AGN feedback model proposed by Booth & Schaye (2009). We shall now briefly summarize these techniques.

2.4.1 Seed particles

In the two main competing SMBH formation models: slow growth from Pop III stars (Madau & Rees 2001) or direct collapse of a low angular momentum halo (Bromm & Loeb 2003; Begelman et al. 2006), the seed SMBH is believed to grow quickly to $10^5 \, M_\odot$. Because our limited resolution, we cannot choose an arbitrary high density threshold, otherwise SMBH will never form. On the other hand, because star formation is a very inefficient process, large enough galaxies devoid of SMBH will always reach this gas density threshold and trigger SMBH seeding.

For these conditions to be fulfilled, we create a sink particle of fixed mass $M_s = 10^5 \, M_\odot$. These particles represent our seed black holes. Note that our third condition ensures that seed black holes form in the nuclear region of star forming disks, where the gas density is probably much larger than 1 H/cc. Because our limited resolution, we cannot choose an arbitrary high density threshold, otherwise SMBH will never form. On the other hand, because star formation is a very inefficient process, large enough galaxies devoid of SMBH will always reach this gas density threshold and trigger SMBH seeding.

2.4.2 Sink particle evolution

Each black hole is considered as a sink particle, as defined in Krumholz et al. (2004). We recall briefly the method here. We consider around each sink a sphere of fixed physical radius $r_{\text{sink}} = 4\Delta x$, where $\Delta x$ is our spatial resolution in physical units, so that $r_{\text{sink}} \simeq 4$ kpc (resp. 2 kpc) for the low (resp. high) resolution run. We assume that the SMBH mass distribution inside the sink is homogeneous, and this homogeneous sphere is added to the total mass density when solving for the Poisson equation. The sink particle is then advanced in time by interpolating the gravitational force back to the sink position using the inverse CIC scheme. For each sink, we compute the Bondi-Hoyle accretion rate

$$\dot{M}_{\text{BH}} = \alpha_{\text{boost}} \frac{4\pi G^2 M_s^2 \rho}{(c_s^2 + u^2)^{3/2}}$$

where $\rho, c_s$, and $u$ are the average gas density, sound speed and relative velocity within the sink radius. These average quantities are computed following the scheme proposed by Krumholz et al. (2004). The parameter $\alpha_{\text{boost}}$ was introduced by Springel et al. (2005) to account for unresolved multiphase turbulence in the SMBH environment. Although this parameter was first chosen constant at $\alpha_{\text{boost}} \simeq 100$ (Springel et al. 2005), Booth & Schaye (2009) argued that this parameter should be close to one in low density regions, while its value should increase in high density regions, in order to match the subgrid model used for the unresolved turbulence in the disks. Based on extensive numerical experiments, they proposed the following phenomenological model to boost Bondi-Hoyle accretion.

$$\alpha_{\text{boost}} = \left( \frac{n_H}{n_*} \right)^2 \text{ if } n_H > n_* = 0.1 \, \text{H/cc},$$
$$\alpha_{\text{boost}} = 1 \text{ otherwise.}$$

Note that this model has no real physical justification, and that it depends crucially on the underlying EOS model. We have been very careful in using this boost factor in conjunction with the same EOS model (see Equ. 1) as in Booth & Schaye (2009).

As advocated by Springel et al. (2005), the accretion rate onto the SMBH cannot exceed its Eddington limit given by

$$\dot{M}_{\text{ED}} = \frac{4\pi G \mathcal{M}_* \rho}{\epsilon_{\tau} \sigma_{T \text{C}}} \text{ with } \epsilon_{\tau} \simeq 0.1,$$

so that the final accretion rate is computed using $\dot{M}_{\text{acc}} = \min(\dot{M}_{\text{BH}}, \dot{M}_{\text{ED}})$. At each time step, a total gas mass of $\dot{M}_{\text{acc}} \Delta t$ is removed from all cells within the sink radius, with the same weighting scheme as the one used to define average quantities (Krumholz et al. 2004). In order to prevent the gas density to vanish or become negative, we allow a maximum of 50% gas removal at each time step.

2.4.3 AGN feedback

In the proposed model for SMBH growth, a key ingredient is the associated feedback model. As demonstrated by many authors (Silk 1974; Fabian et al. 2000; McNamara et al. 2001), the physical processes at the origin of this energy injection are still unclear: radiative feedback (Ciotti & Ostriker 2001), cosmic rays (Breggen et al. 2004), and strong shocks (see the review

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of Begelman (2004). A common property of various models is that they require a very good spatial resolution to be captured realistically in hydrodynamical simulations. The most advanced modeling so far has been using AGN-driven jets (Churazov et al. 2001; Reynolds et al. 2001; Omma et al. 2004; Ruszkowski et al. 2004; Brüggen et al. 2005; Cattaneo & Teyssier 2007), leading to turbulent convective motions and "shocklets" escaping the cluster core (Chandran & Rasera 2007; Rasera & Chandran 2008; Sharma et al. 2009). In some cases, depending on the injected energy, these AGN-driven jets can drive strong shock waves that can travel to very large distances (Baldi et al. 2009). In current cosmological simulations, numerical resolution does not allow these effects to be self-consistently modeled. As it is customary under these circumstances, we rely on a more phenomenological model.

In the cosmological context, the model proposed by Booth & Schaye (2009) appears to be easier to implement than the one proposed by Sijacki et al. (2007). Moreover, it relies on only one main free parameter, the coupling efficiency $\epsilon_c$, that can be calibrated to the observed $M_\ast \sim \sigma$ relation to the fiducial value $\epsilon_c = 0.15$ (Booth & Schaye 2009). We have adapted their model to the RAMSES code, using the following approach: at each time step, we compute the SMBH feedback energy as a fixed fraction of the rest mass energy of the accreted gas, multiplied by the "coupling efficiency" $\epsilon_c$,

$$\Delta E = \epsilon_c \epsilon_f M_{\text{acc}} c^2 \Delta t. \quad (6)$$

This energy is not released immediately in the surrounding gas. It is instead accumulated over many time steps and stored into a new SMBH related variable $E_{\text{AGN}}$, so that we can avoid atomic line cooling to radiate this energy instantaneously. Following the trick proposed by Booth & Schaye (2009), we release this accumulated energy inside the sink radius when

$$E_{\text{AGN}} > \frac{3}{2} m_{\text{gas}} k_B T_{\text{min}} \quad (7)$$

where $m_{\text{gas}}$ is the gas mass within the sink radius and $T_{\text{min}}$ is the minimum feedback temperature. As soon as $T_{\text{min}}$ is chosen above $10^7$ K, the critical temperature below which metal line cooling becomes very efficient, the resulting feedback scheme does not depend on the chosen value for $T_{\text{min}}$. We adopt here $T_{\text{min}} = 10^7$ K. As can be seen on the previous equation, this threshold energy depends directly on the gas density in the environment of the black hole. When dense and cold gas is present, more energy is required to reach the threshold. After enough mass has been accreted, a strong burst of energy is released, that will unbind the surrounding dense gas. On the other hand, when only diffuse, hot gas is present, the threshold energy is much easier to reach, and feedback proceeds in a quasi-continuous fashion. In some sense, based on this rather simple recipe, we can account for both the "quasar mode" and the "radio mode" of the AGN feedback model of Sijacki et al. (2007).

3 RESULTS

In this section, we describe the properties of our simulated cluster for the 3 different models, labelled "SF", "quenching" and "AGN" in most of the Figures. We will focus our analysis in the final mass distribution, and compare, whenever it is possible, to actual Virgo cluster data. The high resolution simulation has only reached $z = 1$ by the time this paper was written. We therefore present mostly low resolution data, although we also compare low and high resolution results to discuss convergence properties.

3.1 SMBH Growth and Feedback

In Figure [1] we show the accretion rate of the most massive SMBH as a function of expansion factor. This plot is relevant only for the "AGN" simulation. Also shown is the Eddington accretion rate, directly proportional to the SMBH mass. It appears quite clearly in this plot that the most massive SMBH grows discontinuously, during very short Eddington limited accretion events, or, at late time, by accreting other black holes, in good agreement with semi-analytical predictions from Malbon et al. (2007). The final mass reaches $M_\ast \approx \times 10^9 M_\odot$ after a last merger around $a \approx 0.85$. In the high resolution simulation (stopped at $z = 1$), the mass evolution is similar, although the predicted SMBH mass at $z = 1$ is almost twice as large. The SMBH mass in M87 has been estimated around $4 \times 10^9 M_\odot$ using dynamical constraints (Macchetto et al. 1997; Gebhardt & Thomas 2000; Gültekin et al. 2009), in very good agreement with our extrapolated prediction. Note that M87 SMBH is close to the $M_\ast \sim \sigma$ relation (Gültekin et al. 2009). Since the free parameter $\epsilon_c$ was calibrated to $\epsilon_c = 0.15$ by Booth & Schaye (2009) on the $M_\ast \sim \sigma$ relation, our AMR simulation appears to be consistent with their SPH results.

The SMBH activity, quite strong before $z = 1$, declines slightly until the present epoch. In our simulation, this early
activity is due to an early phase of frequent mergers feeding the SMBHs very efficiently. Strong and repeated outbursts of energy are launching strong shock waves in the IGM, rising the IGM entropy within the whole proto-cluster region. This early epoch can therefore be considered as representative of the pre-heating scenario advocated by several authors to explain structural properties of galaxy clusters (Kaiser 1991; Ponman et al. 1999; Babul et al. 2002, Davé et al. 2008). On the other hand, at later epochs ($z < 1$), when the cluster mass is finally assembled, AGN feedback prevent gas from overcooling and from accumulating in the core. This is well illustrated by the sequence of temperature maps shown in Figure 2 just after the strong AGN outburst occurring at $a \approx 0.62$ (see Fig. 4). The first image show the mass-weighted projected temperature within the whole cluster, just at the time of the outburst. Slightly after (in the second frame), the whole cluster has been significantly heated, with buoyantly driven plumes of hot gas escaping the cluster core (Chandran & Rasera 2007, Cattaneo & Teyssier 2007, Rasera & Chandran 2008, Sharma et al. 2009). In the next frame, a strong shock, visible as a sharp temperature discontinuity, develops close to and beyond the virial radius. The last frame shows the cluster back to hydrostatic equilibrium, waiting for the next AGN outburst.

Although the feedback recipe doesn’t explicitly account for it, the AGN energy deposition typically proceeds in two modes: a strong, energetic mode or “quasar mode”, which in our case corresponds to the Eddington luminosity and reaches $5 \times 10^{46}$ erg s$^{-1}$, and a quiescent mode or “radio mode”, with a Bondi-Hoyle-limited luminosity of $5 \times 10^{41}$ erg s$^{-1}$. If we now take into account the coupling efficiency parameter $\epsilon_c = 0.15$ in our energy estimate, we obtain a total luminosity of $9 \times 10^{40}$ erg s$^{-1}$ during radio mode. The X-ray luminosity of the active nucleus of M87 observed with Chandra is $L_{X, 0.5-7 \text{ keV}} \approx 7 \times 10^{40}$ erg s$^{-1}$ (Matteo et al. 2003). The fact that our simulated black hole

Figure 2. Maps of the mass weighted temperature of the simulated cluster at four different redshifts. The first redshift in the series corresponds to the strong SMBH outburst seen in Figure 1 around $a \approx 0.62$. 

### References

- Kaiser, 1991
- Ponman et al., 1999
- Babul et al., 2002
- Davé et al., 2008
- Chandran & Rasera, 2007
- Cattaneo & Teyssier, 2007
- Rasera & Chandran, 2008
- Sharma et al., 2009
- Matteo et al., 2003
properties match well observational constraints of M87 is of great importance: it means that the rest mass energy released by the black hole into the forming cluster over its entire history is consistent with M87. The other properties of our simulated Virgo cluster, and in particular the mass distribution in stars, gas and dark matter, are therefore predictions of the model, and not the result of some fitting process.

3.2 The mass distribution of stars and gas

We have plotted in Figure 3 the surface brightness of our simulated Virgo cluster in the SDSS i band. One clearly sees many satellite galaxies orbiting around the BCG and a rich structure in the intracluster light component. In the SF case, the BCG appears as a very bright, gas rich and disc-like object. We have also plotted in Figure 4 the stellar mass profile from this SF simulation: we see immediately that the BCG stellar mass (measured at 20 kpc from the centre) is a factor of 10 to large, when compared to the observational estimate of Gebhardt & Thomas (2009). This is the classical result of the over-cooling problem that occurs for cluster simulations with standard galaxy formation physics. Our second scenario, the Quenching run, partially alleviates this problem. As can be seen on the surface brightness maps (Fig. 3), the BCG and the most massive satellites are now much dimmer. The stellar mass profile in Figure 4 is in much better agreement with observations, although still slightly larger. When one looks now at the gas distribution in the cluster, it becomes quite obvious that this Quenching scenario is far from being a viable solution. We have plotted in Figure 4 the mass-weighted, projected gas density. We see a massive gas clump in the cluster core for both the SF and the Quenching runs. For sake of comparison, we have plotted the simulated gas density profiles for our simulations and the best-fit $\beta$-model for M87 from Churazov et al. (2008). The gas density is the SF run is a factor of 100 too large in the core of the cluster, and it is even worse for the Quenching scenario, by an additional factor of 2. We therefore conclude that for both SF and Quenching models, the simulated cluster suffers from a strong overcooling problem, with the build up of a dense, concentrated BCG, for which the stellar mass or the gas mass (or both) are in far in excess of those observed in M87.

We now turn to the analysis of our AGN model. The stellar surface brightness map is by far the dimmest of our 3 models: star formation has been dramatically reduced, even more than our Quenching scenario. The stellar mass profile is now below the observational constraints by a factor of 3 at 100 kpc (see Fig. 4) and there is less apparent structure in the ICL component. AGN feedback has been quite successful in regulating star formation in the cluster. The gas distribution has also been profoundly affected by the SMBH model. First, no large, gas rich disc is visible in the projected gas density map: the overcooling problem have been efficiently removed. We see in Figure 5 that the dense unrealistic gas core has disappeared. When compared to the best-fit $\beta$-model proposed by Churazov et al. (2008) for M87, the agreement is striking. Note that the cooling flow, although dramatically reduced, is still present in the AGN run, and it can be detected as the density enhancement within the central 10 kpc of the cluster. Interestingly, the knee in the gas density profile seen around 10 kpc in our model is also present in the data at $\sim 5$ kpc from the center (Churazov et al. 2008, see Fig. 5 in their paper), suggesting also the presence of a similar cooling flow in M87. Another important difference between the SF/Quenching runs and the AGN run can be seen at large radii in the gas distribution: the gas density in the AGN case is 30% larger, showing that gas have been removed from the core and stored at large radii (beyond the virial radius) by strong shocks similar to the one shown in Figure 2.
Figure 3. Maps of the projected stellar (left panels) and gas (right panels) mass distributions in the simulated cluster at $z = 0$ for our three models.
Table 2. Mass fractions inside the virial radius for our three different models. The universal baryon fraction we used in this paper is 15%.

<table>
<thead>
<tr>
<th>Run</th>
<th>$M_{\text{vir,}200c}$</th>
<th>$I_{\text{gas}}$</th>
<th>$I_{\text{bar}}$</th>
<th>$I_{\text{SF}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF</td>
<td>$1.2 \times 10^{14} M_\odot$</td>
<td>16%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>Quenching</td>
<td>$1.2 \times 10^{14} M_\odot$</td>
<td>16%</td>
<td>3%</td>
<td>13%</td>
</tr>
<tr>
<td>AGN</td>
<td>$1.1 \times 10^{14} M_\odot$</td>
<td>13%</td>
<td>1%</td>
<td>12%</td>
</tr>
</tbody>
</table>

Figure 6. Effect of the mass resolution on the stellar mass profiles from our AGN model. The blue line is the stellar mass profile of M87 from Gebhardt & Thomas (2009).

3.3 The effect of mass resolution

Using our high resolution simulation with AGN feedback, we would like to estimate the effect of numerical resolution on our results. Since this expensive calculation was not completed at the time of this work, we only report our analysis at $z = 1$. We see in Figure 6 the stellar mass profiles for the low and the high resolution runs. For comparison are also shown the final mass profile ($z = 0$) for the low resolution run and the observed stellar mass distribution. Contrary to what is often claimed in the literature, we do see a strong effect of mass (and spatial) resolution in the stellar mass distribution. The effect is stronger for the BCG close to the center (the stellar mass has increased by a factor of 8 at 10 kpc) than for the cluster as a whole (the total stellar mass within the virial radius has increased only by a factor of 2 at $z = 1$). The effect of mass resolution is smaller for the other components (gas and dark matter).

The strong effect of mass resolution on the star formation history of the simulated halo can be interpreted easily by comparing the minimum resolved halo mass (optimistically set to 100 dark matter particles) to the minimum mass for star forming halos based on atomic cooling arguments (Gnedin 2004; Rasera & Tevssier 2006; Hoeft et al. 2006). This minimum mass (also referred to as the Filtering Mass) starts around $10^7 M_\odot$ before reionization and then rises steadily as $(1 + z)^{3/2}$ from redshift 6-7 to the final epoch. Resolving this minimum mass before reionization will require a dark matter particle mass below $10^5 M_\odot$, a rather strong requirement for cluster-scale cosmological simulation. A more flexible criterion based on resolving the majority ($\sim 80\%$) of star forming halos gives a less stringent limit around $M_{\text{min}} \approx 10^8 M_\odot$ (Iliev et al. 2007). Nevertheless, our low resolution run falls short of the corresponding required dark matter particle mass by 65, while our high resolution run is “only” a factor of 8 above the limit. As explained in Lucia & Blaizot (2007), BCG are “fundamentally hierarchical” objects, that formed their stars very early ($80\%$ before $z = 3$) and assembled late (after $z = 0.5$ in average). This effect is directly related to the suppression of cooling flows and the associated star formation by AGN feedback. This early star formation occurs in rather small mass halos (Lucia & Blaizot 2007) in which star formation proceeds through accretion of diffuse gas in cold streams (Dekel et al. 2009). Although BCGs are quite massive objects, it is of great importance to resolve properly the earliest epoch of star formation, in order to account for all the stellar mass in these objects.

For the low resolution simulation, we see in Figure 6 that the stellar mass profile has evolved only slightly between $z = 1$ and $z = 0$. Inside the BCG, we see stars expanding slightly, while the stellar halo grows in mass more substantially, by almost a factor of 2. This evolution is in good qualitative agreement with the group-scale simulation reported by Feldmann et al. (2010). From this analysis, we can extrapolate our high-resolution simulation down to redshift zero, and acknowledge that the agreement with M87 stellar distribution is very good. We therefore speculate that our model with AGN feedback will converge from below to the correct stellar mass distribution. It is worth stressing that the same analysis can be made for our Quenching run, and that its converged stellar mass will end up being significantly above the observational limit. From this, we conclude that AGN feedback is necessary, not only to regulate star formation inside massive galaxies, but also to destroy and remove the gas supply in satellite galaxies.

3.4 The distribution of dark matter

One important consequence of the overcooling problem is to modify significantly the properties of the dark matter halo. We have plotted in Figure 7 the projected dark matter density for our 3 models, and for the corresponding pure dark matter simulation. We immediately see that the dark halos in the overcooled runs (SF and Quenching) are denser and rounder than the pure dark matter case. With AGN feedback, we basically recover the halo shape and distribution of the pure dark matter case. The effect of gas cooling on the dark halo has been interpreted in term of adiabatic contraction of the particle orbits (Blumenthal et al. 1986; Gnedin et al. 2004), meaning that individual orbits are compressed inward, while conserving the adiabatic invariant $I = rM(< r)$. The global shape change has been also interpreted by Debattista et al. (2008) as a transition from boxy orbits to more circular ones. These effects have been studied quite extensively at galactic scales, where they are probably more relevant (Abadi et al. 2009; Pedrosa et al. 2009). Although we are dealing with a much larger object, we recover very similar properties for our dark halo, because of over-
cooling. We have plotted in Figure 8 the cumulative dark matter mass profiles for our three runs, plus the Dark Matter Only (DMO) simulation. The DMO profile has been multiplied by 85% to allow a direct comparison with the baryonic runs and is very well fitted by a NFW profile with a concentration parameter $c = 7.5$. The fit is shown as the blue dotted line on the same figure. The dark matter profiles for the SF and Quenching runs are very similar, except in the very centre of the cluster. They appear significantly adiabatically contracted. Interestingly enough, the AGN case appears slightly expanded, when compared to the DMO simulation. We will now use AC theory to explain these trends.

Gnedin et al. (2004) have revisited the original paper of Blumenthal et al. (1986) on AC theory, stressing that the original assumption of purely circular orbits was leading to an overestimate of the baryon-induced dark halo contraction. They presented a numerical implementation for their modified AC theory in which the particle orbit distribution was allowed some radial components and predicted the contracted dark matter distribution, given the initial dark matter profile and the final baryonic distribution. We present in the Appendix a simple analytical model to account for the adiabatic contraction of the dark halo, based on Gnedin et al. (2004) theory.

In Figure 8 we have plotted the total baryonic mass $M_{\text{bar}}$ as a function of the final radius for our 3 different models. Although the actual distributions are different from our simple model, we have fitted them using a constant surface density, truncated disc. The fits are very similar in the SF and Quenching case, so we have used only one model with $m_d \approx 5 \times 10^{12} \, M_\odot$ and $r_d \approx 20$ kpc. In this case of strong baryonic concentration, our analytical model with $r_d \ll r_s$ applies: we have plotted the corresponding AC theory prediction in Figure 9 as the dotted line, showing convincingly that the Gnedin et al. (2004) model, in a simplified formulation, works quite well.
AGN and Mass Distribution

Figure 8. Cumulative total baryonic mass profile (gas + stars) in the simulated cluster at $z = 0$. The dotted lines are fits to the measured profiles for our simple model of adiabatic contraction of the dark halo.

Figure 9. Cumulative dark matter mass measured in our three models at $z = 0$. Also shown in blue is the profile we obtained in the dark matter only (DMO) simulation. In each case, the dotted line corresponds to our analytical model of adiabatic contraction. Note that in the AGN feedback case, we see a slight adiabatic expansion of the dark halo.

The AGN feedback model gives us a much more extended baryonic mass profile. We have fitted it using the constant surface density truncated disc model with parameters $m_d \approx 2 \times 10^{12} \, M_\odot$ and $r_d \approx 700 \, \text{kpc}$ (see the quality of the fit in Fig. 8). In this case, the AC prediction cannot be worked out analytically. We have therefore solved for the real root of the third order polynomial defined by Equation [A1] and plotted the result in Figure [8]. Again, the prediction from [Gnedin et al. 2004] theory is very close to the measured dark matter profile. In the AGN feedback case, however, we see that the dark matter has expanded slightly, when compared to the pure dark matter case, and that this "adiabatic expansion" appears to be well captured by the same adiabatic invariant for the orbits of dark matter particle. Note that this expansion is very small, as it affects the dark matter mass distribution by less than a few percent. We have also checked that using the complete numerical solution of [Gnedin et al. 2004] does not affect our conclusions.

A good diagnostic of how much concentrated the simulated halo should be to match the observations is to compare the total mass profile with the one derived from dynamical arguments using M87 optical and X ray data. [Gebhardt & Thomas 2009] have derived a complex mass model for M87, including the presence of a central SMBH, stellar BCG and dark matter halo. Their mass model is compared to our total mass profiles from our three different models in Figure 10. The SF and Quenching models are too much concentrated and overestimate the total mass by a factor of 2 to 4 in the inner 100 kpc. The AGN model is in much better agreement, although slightly below. As we discussed above, the low resolution simulation we analyze here is not fully converged in terms of star formation, so that we expect the central BCG to be more massive, resulting in a better agreement between our AGN model and the observed total mass profile.

Figure 10. Cumulated total mass profile (baryons + dark matter) in the simulated cluster at $z = 0$. The blue line in the is the mass profile deduced from stellar kinematics and X-ray data (Gebhardt & Thomas [2009]).

3.5 The baryon fraction

The most important consequence of the disappearance of the overcooling problem is that we expect the baryonic mass distribution to be in much better agreement with observational constraints. Using X-ray data, it is indeed possible to estimate the gas profile in large clusters, while the stellar mass can be measured using optical data. [Gonzalez et al. 2007] have computed the baryon mass fraction within $r_{500}$ for a large sample of groups and clusters. They have found a...
slight deficit of baryons \( f_{\text{bar}} = 0.133 \pm 0.004 \), when compared to the universal baryon fraction as measured by WMAP \( \Omega_b/\Omega_m = 0.176 \pm 0.008 \) (Spergel et al. 2003, 2007). From Figure 11 we see that the SF and Quenching runs show a slight baryon excess with \( f_{\text{bar}} \approx 0.16 \) while our universal baryon fraction \( \Omega_b/\Omega_m \) was set to 0.15 in our simulation (see Table 2). This is a direct consequence of overcooling (Kravtsov et al. 2003). On the contrary, the AGN model show a clear baryon deficit with \( f_{\text{bar}} \approx 0.13 \), in striking agreement with the observed average value. In our model, this baryon deficit is the consequence of the repeated effect of AGN-driven shocks and convective motions, pushing gas outside the virial radius. One can see from the local baryon fraction profile in Figure 11 that this gas accumulates in a region between 1 to 2 virial radii around the cluster, beyond which the cumulated baryon fraction converge to the universal one.

Our SF model compares very well to the AMR simulation performed by [Kravtsov et al. (2005)], showing a slight excess of baryon at the virial radius. From these standard galaxy formation models, we obtain gas properties that compare favorably to X-ray data (Nagai et al. 2007). We see indeed in Figure 11 that in the SF model, the gas mass fraction is slowly decreasing towards the center, with a significant deficit at the virial radius. This behavior is traditionally explained by the joint effect of cooling and star formation (Voit & Bryan 2001). The price to pay is however to form too many stars and cold gas in the cluster, as confirmed by many previous numerical models (Borgani et al. 2004, Kravtsov et al. 2003, Borgani & Kravtsov 2009). Our simple Quenching model is making things better for the stellar component, but now the gas mass distribution is too concentrated (see Fig. 11). Only with AGN feedback can we obtain a small stellar mass fraction and in the same time the correct gas distribution.

Recently, Puchwein et al. (2010) have simulated a large number of groups and clusters with the SPH code GADGET, using a mass resolution that is only about a factor 2 lower than ours and a spatial resolution of 2.5 kpc (compared to 1 kpc at low res. or 0.5 kpc at high res. here). Nevertheless, they also found that with AGN feedback, the total baryon fraction was below the universal value. More interestingly, they report a stellar mass fraction of \( f_* \approx 0.05 \), quite independent of the parent halo mass. In our case, for our Virgo-like cluster with \( M_{\text{vir}} \approx 10^{14} M_\odot \), we obtained \( f_* \approx 0.01 \) in the low resolution case, a value that can be extrapolated to \( f_* \approx 0.02 \) in our high resolution simulation. Our value is definitely in better agreement with the observational estimate proposed by [Lin et al. 2003, 2004], while the higher value found by Puchwein et al. (2010) is in better agreement with the observations reported in [Gonzalez et al. 2007]. Using the original feedback model of [Booth & Schaye 2009] in the GADGET code, Duffy et al. (2010) have also computed the predicted baryon and stellar mass fraction of a large sample of groups extracted from a cosmological simulation. Although they report a similar baryon deficit within the virial radius, they obtained \( f_* \approx 0.03 \) for a slightly larger universal baryon fraction \( \Omega_b/\Omega_m = 0.18 \). We see that there is a consensus about a strong reduction of the stellar mass fraction in groups and clusters thanks to AGN feedback. The extent of this reduction seems to depend quite sensitively to the details of each implementation, and possibly to the nature of the code (SPH versus AMR). We would like also to stress that all the reported simulations, include ours, are probably not fully converged yet. One key difference between the SPH simulations and ours seems to come from the amount of ICL. We defer this analysis to a companion paper.

4 SUMMARY AND CONCLUSIONS

We have simulated the formation of a Virgo-sized galaxy cluster to study the effects of feedback on the overcooling
problem. The impact of AGN feedback on the distribution of the baryonic mass is strong, and in good agreement with previous SPH simulations: star formation in massive galaxies is drastically reduced. At the same time, left-over gas is very efficiently removed from the core of the parent halos, where it would have otherwise accumulated. In order to quantify the effect of AGN feedback, we have run two other reference simulations: one model with only star formation and supernovae feedback (the standard scenario) and one model for which we have artificially prevented star formation to occur in massive enough spheroids (the quenching scenario).

A detailed comparison of the three models clearly demonstrates that AGN feedback is needed to control star formation in the central BCG, but also to unbind the overcooling gas from the cluster core. We also clearly identify the effect of the baryon dynamics on the dark matter mass distribution on large scale. Interestingly enough, in case of AGN feedback, we observe the adiabatic expansion of the dark halo, an effect well modeled by the AC theory [Gautein et al. (2004)]. A comparison of our simulation results with observational data for Virgo and its central galaxy M87 rules out the standard model, but also the quenching model. On the contrary, our simulation with AGN feedback, although not fully converged yet, shows a very good agreement with M87 data in term of mass distribution. In particular, we obtain a significantly reduced baryon fraction within the virial radius, in agreement with observations compiled by Lin et al. (2003) and Gonzalez et al. (2007). We clearly identify in our simulation that gas is removed from the core of the cluster by convective motions and/or strong shocks, and accumulates in a region just outside the virial radius.

Our cluster formation simulations with AGN feedback have not fully converged yet - as we increase the resolution, we find a stellar mass profile for the BCG that is in better agreement with observations, but it is still too low by about a factor of two. We are still missing the lowest mass galaxy population, which could provide the missing stellar mass in the central elliptical galaxy. We also note that, in the current picture, AGN feedback is a morphologically dependent process: it only directly affects galaxies with SMBHs, i.e. galaxies with a significant bulge/spheroid component. Higher resolution studies would be needed, in order to reliably model this distinction, so that star formation in disky galaxies is not artificially suppressed.

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using the following simplified model

\[ M_i(r_i) = M_{200} \frac{\log(1 + x) - x/(1 + x)}{\log(1 + c) - c/(1 + c)} \]  \hspace{1cm} (A3)  

where \( x = r_i/r_s \) and \( r_s = r_{200}/c \). \( M_{200} \) is the total virial mass. For the baryonic distribution, we assume a constant surface density disc with size \( r_d \) and mass \( M_d \), so that

\[ M_{\text{bar}}(r_f) = m_d \left( \frac{r_f}{r_d} \right)^2 \]  \hspace{1cm} (A4)

The dark matter mass fraction is computed using \( f_d = 1 - M_d/M_{200} \). The model we considered in Equation [A4] for the baryonic mass distribution has been chosen that simple on purpose: inserting Equation [A4] into the AC relation in Equation [A1] one clearly sees that we have to find the only real root of a third order polynomial equation with unknown \( r_f/r_i \). This can be done quite easily with any root finder. In case the disc size is small enough (namely if \( r_d \ll r_i \)), the AC model is fully tractable analytically by noticing that for \( x \ll 1 \), one has \( M_i \propto x^2 \). We therefore have

\[ \frac{r_f}{r_i} = 1 + \alpha \left( \frac{M_i(r_i)}{M_d(r_i) + M_d} - 1 \right) \quad \text{for} \quad r_f \geq r_d \]  \hspace{1cm} (A5)  

\[ \frac{r_f}{r_i} \approx \text{constant} \quad \text{for} \quad r_f < r_d \]  \hspace{1cm} (A6)  

where the constant can be determined by continuity.

**APPENDIX A: ADIABATIC CONTRACTION MODEL**

If one defines the initial radius of each dark matter shell as \( r_i \) and its final, adiabatically contracted value \( r_f \), Abadi et al. (2009) have proposed to capture Gnedin et al. (2004) model using the following simplified model

\[ \frac{r_f}{r_i} = 1 + \alpha \left( \frac{M_i}{M_f} - 1 \right) \quad \text{with} \quad \alpha \simeq 0.68. \]  \hspace{1cm} (A1)

The original Blumenthal et al. (1980) can be recovered using \( \alpha = 1 \). The final cumulated mass distribution is computed using

\[ M_f = M_{\text{dm}}(r_f) + M_{\text{bar}}(r_f) = f_{\text{dm}} M_i(r_i) + M_{\text{bar}}(r_f) \]  \hspace{1cm} (A2)