AGN HEATING AND DISSIPATIVE PROCESSES IN GALAXY CLUSTERS

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ABSTRACT

Recent X-ray observations reveal growing evidence for heating by active galactic nuclei (AGN) in clusters and groups of galaxies. AGN outflows play a crucial role in explaining the riddle of cooling flows and the entropy problem in clusters. Here we study the effect of AGN on the intracluster medium in a cosmological simulation using the adaptive mesh refinement FLASH code. We pay particular attention to the effects of conductivity and viscosity on the dissipation of weak shocks generated by the AGN activity in a realistic galaxy cluster. Our 3D simulations demonstrate that both viscous and conductive dissipation play an important role in distributing the mechanical energy injected by the AGN, offsetting radiative cooling and injecting entropy to the gas. These processes are important even when the transport coefficients are at a level of 10% of the Spitzer value. Provided that both conductivity and viscosity are suppressed by a comparable amount, conductive dissipation is likely to dominate over viscous dissipation. Nevertheless, viscous effects may still affect the dynamics of the gas and contribute a significant amount of dissipation compared to radiative cooling. We also present synthetic Chandra observations. We show that the simulated buoyant bubbles inflated by the AGN, and weak shocks associated with them, are detectable with the Chandra observatory.

Subject headings: galaxies: active - galaxies: clusters: cooling flows - X-rays: galaxies

1. INTRODUCTION

Clusters of galaxies are good laboratories for studying the interaction of outflows from active galactic nuclei with the ambient intracluster medium (ICM). Recent observational evidence demonstrates that the lives of AGN and galaxy clusters in which they reside are closely intertwined. In particular, there is mounting observational evidence that AGN may provide a vital clue in explaining the cooling flow problem. The gas in the cool cluster cores should cool and accrete at rates of 10 to 1000 solar masses per year. However, this is in conflict with observational evidence. Moreover, the gas temperatures in cluster centers are typically maintained above ~ 2 keV. As many cooling flow clusters are known to harbor active radio sources (Burns 1990, Eilek 2004) and the enthalpy of cavities inflated by radio galaxies scales with the cooling flow luminosity (Birzan et al. 2004), AGN may serve as a viable heating source to prevent the gas from cooling and accreting at excessive rates. Direct evidence for AGN heating has indeed been found in recent studies. Observations of the Perseus cluster (Fabian et al. 2003a,b) and the Virgo cluster (Forman et al. 2004) reveal sound waves and weak shocks in the ICM. Even more recently, Nulsen et al. (2004) found evidence for shock heating in Hydra A, McNamara et al. (2004) in MS0735.6+7421 and Sanderson, Finoguenov & Mohr (2004) in Abell 478. These results strongly suggest that AGN outflows can heat the ICM in a spatially distributed fashion, which may help to maintain ICM stability against radiative cooling.

The evidence for non-gravitational heating in clusters has also been observed in a statistical sense in cluster scaling relations. These relations show departures from the self-similar scalings and reveal systematic excess of entropy (e.g., Ponman, Sanderson & Finoguenov 2003). In a recent study, Croston et al. (2004) separated a sample of groups into radio quiet and radio loud objects. They demonstrated that radio loud groups deviate from self-similarity. This result demonstrates that AGN play a crucial role in heating the ICM and may offer the solution to the entropy excess problem.

Based on observations of the Perseus cluster it first has been suggested by Fabian et al. (2003a,b) that viscosity may play an important role in dissipating energy injected by the central AGN. This idea has been tested in numerical simulations by Ruszkowski et al. (2004a,b) and Reynolds et al. (2005). Apart from viscosity, thermal conduction has been considered by a number of authors as means of transferring energy from hot outer layers of clusters towards the cool cluster cores (e.g., Fabian, Voigt, & Morris

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2. Initial conditions and the simulation setup

The initial conditions for our simulations were computed with the SPH code GADGET in standard ΛCDM cosmology (ΩΛ = 0.7, Ωm = 0.3, h = 0.7). They are based on a re-run of the S2 cluster in Springel et al. (2001). At redshift z = 0 this cluster has a mass of 7 · 10¹⁴ M⊙. The initial density (right panel) and temperature (left panel) slices through the cluster center are shown in figure 1. One can clearly see that this cluster is quite dynamic and shows a lot of substructure. It can also be seen in the temperature map that the central part of the cluster shows a cool core characteristic of cooling flow clusters.

The SPH simulation of the cluster includes radiative cooling and star formation. The output of the SPH simulation serves as initial model for our adaptive mesh refinement (AMR) simulation. We use the FLASH code which is a modular block-structured AMR code, parallelised using the Message Passing Interface (MPI) library. It solves the Riemann problem on a Cartesian grid using the Piecewise-Parabolic Method (PPM) and, in addition, includes particles that represent the collisionless dark matter. The particles are advanced using a cosmological variable-timestep leapfrog-method. Our simulations included 714346 collisionless particles that represent stars and dark matter. Gravity is computed by solving Poisson’s equation with a minimal level of refinement was set to 3 which means that the minimal grid contains 16 · 2³(3−1) = 6⁴ zones. The maximum level of refinement was 7, which corresponds to an effective grid size of [16 · 2(7−1)]³ = [1024]³ zones or an effective resolution of 1.96h⁻¹ kpc. The code was run on 64 processors of the IBM p690 at the NIC Centre in Jülich, Germany and at the National Center for Supercomputing Applications at the University of Illinois on an identical machine.

3. Heating

3.1. The energy and momentum equations

The evolution of internal energy is followed by solving the energy equation

\[ \rho \frac{de}{dt} = -p \Delta + \rho \dot{\varepsilon}_{\text{visc}} + \frac{\partial}{\partial x_i} \left( \kappa \frac{\partial T}{\partial x_i} \right), \]

where \( \kappa = 5.0 \times 10^{-7} (\ln \Lambda / 3) - 1 T^{5/2} f_c \) (Spitzer 1962) is the conductivity coefficient and \( f_c \) is the conductivity suppression factor. The dissipation of mechanical energy due to viscosity, per unit mass of the fluid, is given by (Batchelor 1967, Shu 1992, Landau & Lifshitz 1997)

\[ \dot{\varepsilon}_{\text{visc}} = \frac{2\mu}{\rho} \left( e_{ij} e_{ij} - \frac{1}{3} \Delta^2 \right), \]

and where \( \Delta = e_{ii} \) and

\[ e_{ij} = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right), \]

and where \( \mu \) is the dynamical coefficient of viscosity. We use the standard Spitzer viscosity for an unmagnetized plasma (Braginskii 1958), for which \( \mu = 6.0 \times 10^{-17} (\ln \Lambda / 3) - 1 T^{5/2} f_v \) g cm⁻¹ s⁻¹, where \( f_v \) is the viscosity suppression factor. We assume that both \( f_v \) and \( f_c \) are equal to 0.1. As conditions inside the buoyantly rising bubbles are very uncertain and because we want to focus on energy dissipation in the ambient ICM, we assume that dissipation occurs only in regions outside the bubbles. To this end we impose a condition that switches on viscous and conductive effects provided that the fraction of the injected gas in a given cell is smaller than 10⁻¹.

Velocity diffusion was simulated by solving the momentum equation

\[ \frac{\partial (\rho v_i)}{\partial t} + \frac{\partial}{\partial x_k} (\rho v_k v_i) + \frac{\partial P}{\partial x_i} = \rho g_i + \frac{\partial \pi_{ik}}{\partial x_k}, \]

where

\[ \pi_{ik} = \frac{\partial}{\partial x_k} \left[ 2\mu \left( e_{ik} - \frac{1}{3} \Delta \delta_{ik} \right) \right] \]

and where all other symbols have their usual meaning.

3.2. Energy injection by AGN

The AGN is assumed to sit in the centre of the cluster. The intermittency period of the AGN, i.e. the period between two subsequent bursts, was set to 3 · 10⁷ years, within which the AGN was active only for a period of 5·10⁵ years. This choice was made in order to produce a number of strong waves in quick succession in order to gauge the
dissipated energy within a feasible simulation time. The time-averaged luminosity of the AGN was \(8.3 \times 10^{44} \text{ erg s}^{-1}\) and the energy was injected into two spherical regions of radius 13 kpc that lie at a distance of 30 kpc on either side of the centre of the cluster. This was done to simulate a bipolar outflow that is typically seen in clusters that show signs of AGN activity. The energy is injected by increasing the internal energy of the gas inside the injection region. We do not alter the velocity of the gas inside the injection region.

3.3. Dissipation of the injected energy

The main transport processes responsible for the dissipation of the injected energy that we consider in this paper are viscosity and conductivity. Below we discuss their relative importance in the case of an unmagnetized plasma.

Viscosity of the gas is due to off-diagonal terms in the stress tensor in the Navier-Stokes equations and, as such, is related to the momentum transport. From order of magnitude estimates we get that viscous forces \(\sim \mu v_{\text{gas}}/l^2\), where \(v_{\text{gas}}\) is the typical gas velocity, \(l\) is the lengthscale over which the gas properties change and \(\mu\) is the coefficient of viscosity. This coefficient is approximately given by \(\mu \sim \nu_i \lambda_i m_i n\), where \(n\) is the number density of gas particles, \(\nu_i\) is a typical velocity of species \(i\) (either electrons \(e\) or protons \(p\)) and \(\lambda_i\) and \(m_i\) are their deflection length and mass, respectively. The deflection length is independent of \(m_i^2\) (e.g., Frank, King and Raine 1995). Since \(\nu_i \propto m_i^{-1/2}\), this implies that the coefficient of viscosity is \(\mu \propto m_i^{1/2} \propto m_p^{1/2}\) and that the transport of momentum and viscosity are dominated by protons.

Both electrons and protons carry the same amount of energy. As electrons move faster than protons by \((m_p/m_e)^{1/2}\), the transfer of heat is mostly due to electrons. Thus, conductivity is dominated by electrons and the coefficient of conductivity is \(\kappa \propto m_e^{-1/2}\).

Let us now compare the relative contribution to dissipation from the above two processes. From order of magnitude estimates (c.f. equations 1 and 2) we have that \(Q_{\text{cond}} \sim (\kappa/k_B) \epsilon_{\text{int}}/l^2\) and \(Q_{\text{visc}} \sim (\mu/m_p) \epsilon_{\text{kin}}/l^2\), where \(\epsilon_{\text{int}}\) and \(\epsilon_{\text{kin}}\) are the internal and kinetic energies of the gas and \(k_B\) is the Boltzmann constant. Equipartition ensures that the kinetic and internal energies are comparable. Thus, \(q \equiv Q_{\text{visc}}/Q_{\text{cond}} \sim (k_B/m_p)(\mu/\kappa) \propto (m_e/m_p)^{1/2}\).

In an idealized case of plane linear waves in a uniform background and without gravity the ratio of viscous to conductive dissipation turns out to be

\[
q = \frac{4}{3} \frac{\mu}{\kappa} \left( \frac{1}{c_v} - \frac{1}{c_p} \right)^{-1},
\]

where \(c_v\) and \(c_p\) are the specific heat at constant volume and pressure, respectively (Landau & Lifshitz, 1997). Substituting values appropriate for a fully ionized hydrogen plasma \(q = 4.2(m_e/m_p)^{1/2} \sim 0.1\) (Braginskii 1958, Spitzer 1962). Thus, in the average sense, the effect of conductivity should dominate over viscosity in terms of the energy dissipation. In other words, this says that the ratio of the Péclet number to the Reynolds number is small. In the presence of magnetic field, both, viscosity and conductivity are thought to be suppressed. However, the Larmor radius of ions is \((m_i/m_e)^{1/2}\) times larger that the Larmor radius of electrons of the same temperature. This can increase the Péclet number relative to the Reynolds number but their ratio may to exceed unity.

We point out that, in this idealized case, the dissipation length due to conductivity is shorter than that due to viscosity.

\[\rho \cdot v \cdot \text{pressure} \]

\[\text{momentum} \rightarrow \text{energy} \]

\[\mu \cdot \kappa \cdot \text{conductivity} \]

\[\kappa = \mu = \frac{1}{2} \text{viscosity} \]

\[\text{viscosity} \rightarrow \text{kinetic} \]

\[c_v \cdot c_p \cdot \text{specific heat} \]

\[q = \frac{4}{3} \frac{\mu}{\kappa} \left( \frac{1}{c_v} - \frac{1}{c_p} \right)^{-1}\]

\[Q_{\text{visc}}/Q_{\text{cond}} \sim (k_B/m_p)(\mu/\kappa) \propto (m_e/m_p)^{1/2}\]
to viscosity by a factor of $q^{-1}$. However, we also note that viscosity still plays a role in “diffusing” the gas momentum by exerting viscous stress forces and affects the overall dynamics of the gas. Also, as demonstrated below, the regions where most of the conductive and viscous dissipation take place do not have to be spatially overlapping, i.e., some regions can be dominated by viscous or conductive dissipation.

The dissipation of mechanical energy injected by the AGN can be estimated as follows. Assuming that the temperature varies smoothly with position in the fluid, the rate of change of mechanical energy can be written as

$$\int_V \dot{\epsilon}_{\text{mech}} dV = \int_V T \frac{dS}{dt} dV = \int_V \dot{\epsilon}_{\text{visc}} dV$$

$$+ \int_S \kappa \nabla T \cdot dS + \int_V \frac{\kappa}{T} \left( \nabla T \right)^2 dV \quad (7)$$

For random temperature fluctuations and $|\nabla T| \gg \Delta T/L$, where $\Delta T$ is the mean temperature change over some typical length $L$, the second term on the right hand side is small compared to the last one if we take the spatial average of equation 7. In particular, for temperature fluctuations, such as waves, that occur in a constant background temperature, this term will vanish when averaged over one wavelength. In other words, if the temperature gradient is dominated by temperature changes on small scales, we may locally approximate the dissipation of mechanical energy by the last term in equation 7. This is the approach that we adopted when comparing the dissipation due to viscosity and conductivity with the radiative cooling.

The simulations of the effects of viscosity and conductivity in three dimensions require high spatial resolution. This can be achieved at the expense of a relatively short simulation time (a few full AGN activity cycles). We point out that the timestep imposed by the transport coefficients on the simulation scales as $(\Delta x)^2 / (\kappa, \mu)$, where $\Delta x$ is the simulation resolution. As this timestep scales more strongly with $\Delta x$ than the standard hydrodynamical Courant condition, and because the transport coefficients depend strongly on temperature, the constraints on the timestep are more stringent that the ones obtained from the standard condition. This is why we chose to resort to comparing instantaneous rates of heating instead of evolving the system for a longer time at lower spatial resolution as the latter could prevent us from capturing essential physics. However, we note that the actual evolution of the gas in the simulations, including the energy transfer and dissipation, does use the above approximation. We also point out that the actual heating of the cluster core is greater than that estimated from this prescription. This is because the spatially and temporally averaged temperature gradient in a cooling flow cluster is positive within the cooling radius and the heat transfer from the hot outer layers will take place. Thus, the estimated conductive dissipation can be considered to be a lower limit on the actual dissipation due to conductivity.

4. SYNTHETIC CHANDRA OBSERVATIONS

We have performed synthetic X-ray observations of the grid at two stages of bubble evolution. These observations simulate a 200ks ACIS-S3 exposure of the (800kpc)$^3$ region centered on the bubble origin. The images are generated by first calculating a MEKAL (Mewe et al. 1985) emissivity at each grid point in three energy bands, then integrating along each line-of-sight through the simulation box in the optically thin limit using the SYNTH code (e.g., Treggillis et al. 2004). The resulting X-ray surface brightness image in each band is modified by galactic absorption, adjusted for the assumed redshift of the simulated cluster ($z=0.0183$, Perseus) then processed through the Chandra ACIS-S3 response function to generate instrument count rates at each pixel of the image. In this case the image plane is larger than the dimensions of ACIS-S3, so we tile the chip accordingly to cover the image plane.

To simulate the effect of the instrumental and X-ray background, we have added the ACIS-S3 D period sky background to the resulting images. The background event file is sorted to generate images in each of the three X-ray bands, then binned to match image resolution, and matched to the exposure of the synthetic observations. To simulate the effect of background subtraction, we have simply mirrored each of the three background images about the vertical chip axis and subtracted the mirrored image in each case. The net counts added and subtracted to the image then are the same, but the counts in each pixel are not identical, resulting in the appearance of a background-subtracted image. The final images have the visual appearance of a Chandra X-ray image. More importantly, in this way we can quantify the expected error level associated with the features in the images.

The final images are equivalent to exposure corrected, background subtracted ACIS-S3 images of the simulated volume. In addition, for the images in each of the three energy bands we have performed an unsharp masking to generate an additional image. This image results from subtracting an image smoothed with a 4 pixel gaussian kernel from the original image. This procedure enhances the appearance of fluctuations about the mean.

5. RESULTS

Figure 2 shows three slices through the cluster center displaying the gas temperature at the time of 140 Myrs (file 0142) after the start of AGN activity. The panels have the size of 2.8 Mpc, 800 kpc and 300 kpc on a side from left to right, respectively. At this stage in the evolution one can clearly identify these bubbles that have not yet reached pressure equilibrium with their surroundings and that are still expanding nearly spherically into the ambient medium (bubbles close to the injection region) as well as older bubbles that have evolved into mushroom-type clouds. As a result of the rapid inflation, the younger bubbles produce a weak shock wave that can be seen to travel outward. Figure 1 also shows that the cluster is quite dynamic, as it shows significant substructure such as clumps and shock fronts.

Figure 3 shows the density distribution in the cluster. This figure corresponds to the same time and box sizes as figure 1. As in figure 1 one can clearly identify the young bubbles that are still in the expansion phase and the older, buoyant bubbles. As expected in the case of weak shocks, the waves are weaker in the density maps than in temperature maps but are still visible.

Figure 4 presents the dissipation rates corresponding to
Fig. 2.— Temperature distribution in a slice through the cluster center. The box sizes in the panels are 2.8 Mpc, 800 kpc, and 300 kpc from left to right, respectively. All panels correspond to the time of 140 Myr after the initial AGN outburst. Both young bubbles still in the inflation phase as well as older buoyantly rising bubbles can be seen. Note nearly spherical weak shocks surrounding the bubbles. All plots are logarithmic and the colorbars show the logarithm of temperature in K.

Fig. 3.— Same as Figure 2 but for physical gas density.

Fig. 4.— Dissipation patterns. All panels are 300 kpc a side and correspond to 80 Myr after the initial outburst of the AGN. Left panel shows the logarithmic ratio of the viscous dissipation and the radiative cooling rate. Middle panel presents the logarithm of the ratio of the conductive dissipation to the radiative cooling rate and the right one presents the logarithm of the ratio of the conductive and viscous dissipation rates.
the time of 80 Myr after the initial AGN outburst. The left panel shows the ratio of the viscous dissipation to the radiative cooling. As can clearly be seen, the weak shocks present in the density and temperature maps are the sites of enhanced dissipation. Some of the strongest waves have dissipation rates comparable to the radiative cooling rates. The middle panel shows the ratio of the conductive dissipation and the cooling rate. A comparison of this and the left panel shows that the conductive dissipation in the shocks on average appears to be higher. This is also visible in the right panel that shows the ratio of the conductive and viscous dissipation rates and especially in the profiles presented below.

Figure 5 is analogous to Figure 4 but corresponds to a later time (140 Myr) after the onset of AGN activity. The dissipation patterns presented in this figure correspond to the same time as the temperature and density maps in Figure 1 and 2, respectively. Comparison of figures 5 and figure 4 shows that the dissipation patterns moved away from the center. The typical speed of these patterns is of order of the sound speed in this cluster. This reinforces the interpretation of these features as sound waves or weak shocks.

Figures 6 and 7 present the profiles of viscous and conductive dissipation for the time of 80 Myr and 140 Myr after the first outburst, respectively. The profiles were extracted along the horizontal lines intersecting the centers of the dissipation maps shown in figures 4 and 6. Left panels present the profiles of the ratios of viscous dissipation and cooling rate. The middle ones are for conductive dissipation and the right panels show the profiles of the ratio of conductive and viscous dissipation. It is interesting to note that the conductive-to-viscous ratios seem to be ~ 10 which is consistent with simple analytic argument presented in Section 3.3.

Figures 8 and 9 show X-ray images of the cluster heated by AGN at the time of 80 Myr and 140 Myr, respectively. The first and the second row show the maps of X-ray surface brightness and unsharped X-ray images, respectively. The columns are for [3.5-7.0] keV [1.5-3.5] keV and [0.3-1.5] keV from left to right. These figures show clear evidence for X-ray features at the spatial locations of the waves resulting from expansion of the bubbles. The bubbles and waves can be clearly seen in the earlier stages in the AGN evolution. All features are more easily detectable in the softer X-ray bands.

Figure 10 shows a closeup of the unsharp masked image in the soft band corresponding to the time of 80 Myr (bottom right panel in Figure 8). Apart from the waves one can easily identify a bow shock wrapping around one side of the maximum in density distribution suggesting a motion to the right.

6. SUMMARY

We have simulated the effects of heating by active galactic nuclei on the intracluster medium including, both, the effect of viscosity and conductivity. This has been done by a high resolution 3D AMR simulation of a galaxy cluster that has been extracted from full a cosmological SPH simulation. Our simulations demonstrate that conductivity is likely to play an important role in dissipating mechanical energy injected by the AGN. We have shown that if the suppression of conductivity and viscosity is of comparable magnitude, then the effect of conductivity on dissipation is likely to exceed that due to viscosity. Nevertheless, viscosity may play a significant role in affecting the dynamical evolution of the buoyant bubbles especially if suppression of conductivity is higher than that of viscosity. The precise values of suppression factors are unknown as yet but we hope that future observations of the ICM would be able to put constraints on their values. We also discuss the detectability of the X-ray features generated by AGN outbursts. Our synthetic data takes into account all instrumental features of the Chandra Observatory and all sources of noise such as X-ray background. We show that bubbles inflated by AGN and the waves generated by the expansion of the bubbles can be seen in these synthetic observations. The detectability of these features depends on the stage in the AGN evolution (with bubbles more easily detectable in the earlier stages) and the Chandra energy band observed (with stronger features in softer bands). Other features such as bow shocks due to substructure motions are also detectable in the simulated X-ray emissivity maps. These are similar to that observed in 1E 0657-56 (Markevitch et al. 2002)

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Fig. 5.— Same as figure 4 but for the simulation time of 140 Myr.

Fig. 6.— Profiles along the horizontal lines through the center of the dissipation patterns in figure 4.

Fig. 7.— Profiles along the horizontal lines through the center of the dissipation patterns in figure 5.
Fig. 8.— X-ray images of the cluster heated by AGN at the time of 80 Myr. First and the second row show the maps of X-ray emissivity and unsharped X-ray images, respectively. The columns are for [3.5-7.0] keV [1.5-3.5] keV and [0.3-1.5] keV from left to right.

Fig. 9.— Same as figure 8 but for the time of 140 Myr.
Fig. 10.— Closeup of the bottom right panel in Figure 8. Both the waves and the bow shock are visible.
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