3D SIMULATIONS OF VISCOS DDISSIPATION IN THE INTRA CLUSTER MEDIUM

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ABSTRACT

We present three-dimensional simulations of viscous dissipation of AGN induced gas motions and waves in clusters of galaxies. These simulations are motivated by recent detections of ripples in the Perseus and Virgo clusters. Although the sound waves generated by buoyant bubbles decay with distance from the cluster center, we show that these waves can contribute substantially to offsetting the radiative cooling at distances significantly exceeding the bubble size. The energy flux of the waves declines more steeply with radius than the inverse-square law predicted by energy conservation, implying that dissipation plays an important role in tapping the wave energy. We show that such dispersing sound waves/weak shocks are detectable as ripples on unsharp-masked X-ray cluster maps, and point out that the interfaces between the intracluster medium and old bubbles are also clearly detectable in unsharp-masked X-ray maps. This opens up the possibility of detecting fossil bubbles that are difficult to detect in radio emission. This mode of heating is consistent with other observational constraints, such as the presence of cool rims around the bubbles and the absence of strong shocks. Thus, the mechanism offers a way of heating clusters in a spatially distributed and gentle fashion as first suggested by Fabian et al. (2003a). We also discuss the energy transfer between the central AGN and the surrounding medium. In our numerical experiments, we find that roughly 50 per cent of the energy injected by the AGN is transferred to the intracluster medium and approximately 40 percent of the injected energy is dissipated by viscous effects and contributes to heating of the gas. The overall transfer of heat from the AGN to the gas is comparable to the radiative cooling losses. The simulations were performed with the FLASH adaptive mesh refinement code.

Subject headings: cooling flows—galaxies: active—waves

1. INTRODUCTION

The long-standing problem of cooling flow clusters of galaxies, in which the central cooling time is much shorter than the Hubble time, is how to prevent the intracluster medium (ICM) from collapsing catastrophically on a short timescale. The original idea for maintaining the overall cluster stability (Fabian 1994) was to postulate that a certain amount of gas decouples from the flow and does not contribute to the cooling of the remaining gas. This model would require up to 1000 $M_\odot$ yr$^{-1}$ in mass deposition rates to guarantee cluster stability. This has been found to be inconsistent with recent Chandra (e.g., McNamara et al. 2000, Blanton et al. 2001) and XMM-Newton observations (e.g., Peterson et al. 2001, 2003; Tamura et al. 2001). Chandra observations reveal a number of clusters with X-ray cavities/bubbles created by the central active galactic nuclei (AGN). It has been suggested by many authors that AGN feedback may play a crucial role in self-regulating cooling flows (e.g., Churazov et al. 2001, Ruszkowski & Begelman 2002, Brighenti & Mathews 2003). One of the main outstanding issues is how the AGN heating comes about in detail. In principle, strong shocks generated by AGN outbursts can dissipate in the ICM and heat the gas. However, imaging observations of cooling flow cores do not give evidence for this mode of heating. Recent Chandra observations of two well-known clusters, the Perseus cluster (Fabian et al. 2003a,b) and the Virgo cluster (Forman et al. 2004), suggest that dissipation of sound waves and weak shocks could be an important source of gas heating — an idea first proposed by Fabian et al. (2003a). Further support for the idea that viscosity may play an important role in the ICM comes from a recent study of density profiles in clusters (Hansen & Stadel 2003). Recently, a number of papers have described simulations of bubble-heated clusters (e.g., Churazov et al. 2001, Brüggen et al. 2002, Brüggen & Kaiser 2002, Brüggen 2003, Quilis et al. 2001). Numerical simulations of viscous dissipation of AGN energy in ICM were previously considered by Ruszkowski et al. (2003) and Reynolds et al. (2004).

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The main purpose of this paper is to extend our previous work on viscous heating of the ICM by waves to three dimensions. The results of a simulation of viscous dissipation in three dimensions could differ from our previous two-dimensional results given that the amplitudes of waves decrease faster with radius in three dimensions. This would directly affect the spatial distribution of the viscous dissipation rate. Three-dimensional calculations also allow us to predict the observational appearance of bubbles and waves. The outline of this paper is as follows. In the next section we describe the assumptions of the model. Section 3 presents and discusses our results, focusing on the spatial distribution of heating. In particular, we discuss the detectability of the ripples/sound waves, their decay rate with distance from the center/bubble surface, determining the gravitational acceleration as a function of the distance from the cluster center $r$ is given by

$$g(r) = 4\pi G\rho_{\text{crit}}\delta \varepsilon x^{-2} \left[ -\ln(1 + x) + \frac{x}{1 + x} \right],$$

(1)

where $r_{\varepsilon} = 100$ kpc is the core radius, $x = r/r_{\varepsilon}$, $\delta = 3.0 \times 10^4$ is the central overdensity, and $\rho_{\text{crit}} = 3H^2_0/(8\pi G)$ is the critical density of the Universe (we assume $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$). The initial temperature distribution is given by

$$T(r) = T_0 \left( 1 + \frac{r}{r_0} \right)^\beta,$$

(2)

where $T_0 = 3.0$ keV, $r_0 = 10$ kpc and $\beta = 0.22$. The temperature at 100 kpc is 5.1 keV. The central electron number density is $2.8 \times 10^{-2}$ cm$^{-3}$. The electron number density at 100 kpc is approximately $5.3 \times 10^{-3}$ cm$^{-3}$. This corresponds to a central cooling time of $\sim 1.3 \times 10^9$ years and a cooling time of $\sim 1.0 \times 10^{10}$ years at 100 kpc. These are values typical of a cooling flow cluster as the central cooling time is much shorter than the Hubble time. We assume that the gas is fully ionized and characterized by $X = 0.75$ and $Y = 0.25$, where $X$ and $Y$ are the hydrogen and helium fractions. The gas obeys a polytropic equation of state with an adiabatic index of $\gamma = 5/3$.

Calculations were done in three dimensions in Cartesian geometry using the PPM adaptive mesh refinement code FLASH (version 2.3). Starting from a single top-level block and using block sizes of $16^3$ zones we allowed for 5 levels of refinement, giving an effective number of $256^3$ zones. The size of the computational domain was $(200 \text{kpc})^3$, which corresponds to an effective resolution of $\sim 0.8 \text{kpc}$. As previously, we employed outflow boundary conditions on all boundaries.

\section{2. Assumptions of the Model}

\subsection{2.1. Initial Conditions}

The initial conditions assumed for our simulation are very similar to those in Ruszkowski et al. (2003); we briefly summarize them here. The ICM is initially assumed to be in hydrostatic equilibrium in an NFW potential (Navarro, Frenk & White 1995, 1997) for which the gravitational acceleration as a function of the distance from the center is given by

$$g(r) = 4\pi G\rho_{\text{crit}}\delta \varepsilon x^{-2} \left[ -\ln(1 + x) + \frac{x}{1 + x} \right],$$

where $r_{\varepsilon} = 100$ kpc is the core radius, $x = r/r_{\varepsilon}$, $\delta = 3.0 \times 10^4$ is the central overdensity, and $\rho_{\text{crit}} = 3H^2_0/(8\pi G)$ is the critical density of the Universe (we assume $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$). The initial temperature distribution is given by

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\subsection{2.2. Heating}

We model AGN heating by injecting hot gas into two regions of radius 3 kpc located 10 kpc to either side of the cluster center. The energy injection rate, $L$, for each source and the mass injection rate per unit volume, $\dot{\rho}$, are both constant while the AGN is in an “on” state. Thus, the energy injection rate per unit mass $\dot{\epsilon}$ is computed from

$$\dot{\epsilon} = \frac{L}{\rho V} - \frac{\dot{\rho}}{\rho},$$

(3)

where $V$ is the volume of one injection region (of radius 3 kpc). When the source is active, it has a constant luminosity of $L = 8.0 \times 10^{44}$ erg s$^{-1}$ and the rate at which mass is injected into the active region is $\dot{\rho}V = 2.8 \times 10^4$ yr$^{-1}$. The energy injection is intermittent with a period of $3 \times 10^7$ years, within which the source is active for $0.5 \times 10^7$ years. Thus, since there are two active regions in the source, the time-averaged luminosity is $\sim 2.7 \times 10^{44}$ erg s$^{-1}$ in the initial state for each activity episode, the temperature and density are a hundred times higher and lower, respectively, than the temperature and density in the initial unperturbed state at the same location.

The dissipation of mechanical energy due to viscosity, per unit mass of the fluid, was calculated from

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

(4)

(Batchelor 1967, Shu 1992), where $\Delta = e_{ij}$ and

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

(5)

and where $\mu$ is the dynamical coefficient of viscosity. We use the standard Spitzer viscosity for an unmagnetized plasma (Braginskii 1958), for which $\mu = 7.1 \times 10^{-17} (\ln \Lambda/31)^{-1} T^{5/2} \text{g cm}^{-1} \text{s}^{-1}$. 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 the regions surrounding the buoyant gas. To this end we impose a condition that switches on viscous effects provided that the fraction of the injected gas in a given cell is smaller than $10^{-3}$. We point out that the value of viscosity in the ICM, just as any other transport parameters such as, e.g., thermal conduction, is highly uncertain, and especially the role of magnetic fields is unclear.

We implemented a fully compressible version of the viscous velocity diffusion equation in the FLASH code. Velocity diffusion was simulated by solving the momentum equation

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

(6)

where

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

(7)

and where all other symbols have their usual meaning.
2.3. Cooling

We switched off radiative cooling because the initial cooling time in the center is longer than the overall duration of the simulation. However, we calculate the radiative cooling rates in order to compare them with the viscous heating rates. For this purpose we use the fit to the cooling function by Tozzi and Norman (2001), which is based on detailed calculations by Sutherland and Dopita (1993)

$$n_1^2\Lambda = [C_1(k_B T)^{n_1} + C_2(k_B T)^{n_2} + C_3]n_e n_e,$$ (8)

where $n_1$ is the ion number density and the units for $k_B T$ are keV. For an average metallicity $Z = 0.3 Z_\odot$, the constants in equation (8) are $\alpha = -1.7$, $\beta = 0.5$, $C_1 = 8.6 \times 10^{-3}$, $C_2 = 5.8 \times 10^{-2}$ and $C_3 = 6.4 \times 10^{-2}$ and we can approximate $n_1 n_e = (X + 0.5 Y)(X + 0.25 Y)(\rho/m_p)^2$. The units of $\Lambda$ are $10^{-22}$ erg cm$^{-3}$ s$^{-1}$.

Thus the main differences from our 2D setup — apart from a coarser resolution — are that we use a uniform adiabatic index, larger injection regions, different luminosities and mass injection rates and a Coulomb logarithm more appropriate for the ICM.

3. Results

The top row in Figure 1 shows X-ray maps of the heated cluster. The panels show five different epochs from earliest on the left to the latest on the right. We assumed that the main contributor to X-ray emissivity is free-free emission. The maps correspond to emission integrated in the energy band $E \in (2 - 10)$ keV. The axis of injection is located in the plane of the sky. The emissivity contrast between the injected material and the surrounding medium is strongest at the center. As the bubbles rise buoyantly in the cluster atmosphere, the contrast diminishes and so does the probability of detecting the bubbles.

The middle row in Figure 1 presents unsharp-masked X-ray images corresponding to the images on the top row. These images were generated by smoothing the original X-ray map and subtracting the original X-ray map. Smoothing was done by convolving the original image with a Gaussian filter centered on a given point. The full width at half maximum of the adopted Gaussian distribution was $\sim 6$ kpc. It is evident from this figure that ripples outside bubble locations are visible. As discussed below, these perturbations are the sound waves/weak shocks. Note also that the interfaces between the bubble location and the ICM are clearly present in these maps. This means that the ripples in the Perseus cluster can be due to a combination of sound waves, weak shocks and interfaces between the ICM and fossil bubbles.

The bottom row in Figure 1 shows the viscous dissipation rate (erg s$^{-1}$g$^{-1}$) associated with the dispersing waves seen in the middle row. These maps show cross-sections through the cluster center that are perpendicular to the line of sight.

In Figure 2 we show the ratio of the viscous heating rate to the radiative cooling rate as a function of time for a range of radii. More distant regions are heated at later times and hence the curves corresponding to these regions rise at later times. It is interesting to note that the heating-to-cooling ratio is of order unity even for more distant regions close to the cooling radius. Thus, heating is well distributed spatially, even though the bubbles occupy a smaller volume than the waves. Note that the curves exhibit a clear periodic behavior which is due to the intermittency of the central source.

Figure 3 shows the ratio of viscous heating to radiative cooling rate as a function of distance from the cluster center for equally-spaced time intervals of $\Delta t = 10^7$ yr until $2 \times 10^8$ yr. As time increases the curves start to decline at progressively larger radii. From this figure one can also deduce the characteristic speed of the wave pattern which we found to have a Mach number of $\sim 1.3$. Thus, the waves can be interpreted as strong sound waves or weak shocks. In the weakly nonlinear regime, the speed of the wave is $c_s (1 + [(\gamma - 1)/2] \alpha)$, where $c_s$ is the sound speed and $\alpha \sim \delta \rho/\rho$ is the normalized wave density amplitude (Stein & Schwartz 1972, Mihalas & Mihalas 1984). For the typical amplitudes seen in the simulation, the wave speed of Mach 1.3 is consistent with these estimates.

Figure 4 shows the ratio of the volume-integrated heating rate to the volume-integrated cooling rate as a function of time. Note that this ratio is of order unity. Therefore, this heating mechanism has the potential for significantly affecting the rate at which the gas loses its internal energy or perhaps even offsetting radiative cooling altogether.

In Figure 5 we present the cumulative injected energy $E_{\text{inj}}$ (solid curve), energy contained in the rising bubbles $E_{\text{bubb}}$ (dashed) and the energy transferred to the ICM $(E_{\text{tran}} \equiv E_{\text{inj}} - E_{\text{bubb}}$; dotted). The bubble energy $E_{\text{bubb}}$ is defined as

$$E_{\text{bubb}} = \int_{\text{bubb}} [e_{\text{pot}}(t) + e_{\text{int}}(t) + e_{\text{kin}}(t)]\rho dV - [e_{\text{pot}}(0) + e_{\text{int}}(0)]\rho(2V_0),$$ (9)

where $e_{\text{pot}}$, $e_{\text{kin}}$ and $e_{\text{int}}$ are the gravitational potential, specific kinetic energy density and specific internal energy density, respectively. The $2V_0$ factor is the total volume of the initial injection regions. The integration is performed over the volume of the bubbles. Correspondingly, the bubble energy increases during outbursts and then decreases during dormant phases. The decrease of the energy in the bubbles with time can be attributed to two factors: (i) energy is transferred to the ambient medium via $PdV$ work and because the rising bubble experiences drag from the surrounding gas and (ii) mixing of the bubble and the ICM gas. Recall that the bubble is defined as the region where the fraction of the injected gas is greater than $10^{-3}$. This assures that essentially no energy injected into the bubble is omitted in the calculation of the bubble energy. The contribution to the bubble energy from the gravitational potential is relatively small. Since mixing occurs without a significant change in pressure and the bubble internal energy is proportional to pressure, the change in bubble energy comes mostly from the $PdV$ work done by the bubble against its surroundings and the drag on the bubble from the ambient ICM.

The fraction of the AGN energy that is transferred to the surrounding ICM is plotted in Figure 6 (solid curve). The ratio of viscously dissipated energy to the energy injected by the AGN is plotted as the bottom (dashed) curve in Figure 6. This figure indicates that approximately 50 per cent of the energy injected by the AGN remains in the buoyant bubbles while the rest is transferred to the surrounding
ICM and that about 40 per cent of the injected energy ends up heating the ambient ICM viscously. We point out that not all of the energy that is transferred to the ICM is converted to heat. It is viscous dissipation that is responsible for heating the gas. The fraction of the injected energy that is transferred to the ambient ICM agrees with simple analytical estimates presented in Ruszkowski at al. (2003) and we repeat this argument here for the sake of clarity. Suppose $dQ$ is the heat injected into the cavity, $dW$ the increase in internal energy, $P$ the pressure, $dV$ the change in volume, $dH$ the change in enthalpy and $dV$ the work done on the surroundings. Applying the first law of thermodynamics to the cavities and assuming local pressure equilibrium, $dQ = dU + P dV = dH - V dP = dH$, so that $dW = P dV = \frac{2}{\gamma} dH \approx \frac{2}{\gamma} dQ$. This means that about 40\% of the energy input can be transferred to the ambient medium. Because the cavities are mildly overpressured, the fraction of the input power transferred to the ICM in the actual simulation is a little larger.

In Figure 7 we show the energy flux of the decaying wave corresponding to the initial outburst. The simulation results are denoted by filled squares connected by a solid line. Also shown for reference is the decay profile corresponding to $r^{-2}$. All curves have arbitrary units. The period-averaged wave energy per unit time that is streaming through a surface $S$ in a direction perpendicular to this surface is $L_w \sim (\delta P)^2 S/\rho v_w$, where $v_w$ is the wave speed. In the absence of any dissipation, the energy flux should scale as $\sim r^{-2}$. However, the slope of the energy flux in our simulations is steeper. This means that viscous dissipation plays an important role in tapping the wave energy.

The characteristic dissipation length $l$ can be estimated from $L_w \sim 70 \lambda_0 T_4^{-2}$ kpc, where $\lambda_0 = 10 \lambda_{10}$ kpc, $n = 0.02 n_{0.02}$ cm$^{-3}$ and $T = 4 T_4$ keV (Fabian et al. 2003a, cf. Landau and Lifshitz 1975). The dissipation length can also be estimated from $l \sim (2 \ln(2 \rho_0 r^{-2})/\partial r + 2/r)^{-1}$, where $\rho_0$ is the normalized density amplitude of the wave and can be directly derived from the simulation results. At $r \sim 55$ kpc, the dissipation length is of order 40 kpc, which is qualitatively consistent with the above simple analytical estimates.

We stress that our use of the Spitzer viscosity is meant to be illustrative and may not accurately represent the momentum transport in the magnetized intracluster medium. For one thing, magnetic shear stresses are likely to dominate over molecular viscosity in the transport of bulk momentum. This could either enhance or suppress the dissipation of sound waves, and will almost certainly make the dependence of stress on the velocity field more complicated. For another, in this macroscopic form of momentum transport the rate of dissipation (due to reconnection) would be nonlocally related to the stress tensor. Treatment of these effects will require high-resolution magnetohydrodynamical simulations. Moreover, magnetic fields could introduce effects similar to bulk viscosity, as a result of plasma microinstabilities. In our simulations we neglected bulk viscosity since it vanishes for an ideal gas. We note that bulk viscosity, if present, could dissipate waves even more efficiently. Finally, we have neglected the effects of thermal conduction, which (assuming Spitzer conductivity) could damp the sound waves more quickly than Spitzer viscosity (since the conductive dissipation rate exceeds the viscous one by a factor $\sim 10$ under the simplified assumption that waves are linear and that the gas has constant density and pressure and gravity can be neglected; see Landau and Lifshitz 1975). We point out that, as long as the waves are linear, the nature of the wave decay due to Spitzer viscosity or Spitzer conductivity is the same, i.e., the only change is the constant damping coefficient. Note that the waves considered here are either linear (sound waves) or weakly non-linear (weak shocks) and characterized by a relatively small Mach number. Since conductivity is expected to be suppressed by magnetic fields, a realistic assessment of whether conduction enhances the damping rate of sound waves is beyond the scope of this investigation. If the dissipation rate significantly exceeds the Spitzer value, then the sound waves will be damped more efficiently and only the gas close to the bubbles will be heated efficiently.

We stress that the actual value of the ratio of heating to cooling (Figs. 2–4) depends on the parameters adopted in the model. However, fine tuning may not be necessary. Self-regulation may be provided by feedback between the accretion rate in the cluster center, which may be controlled by the central cooling rate, and the luminosity of the AGN. That is, when the source is in the “on” state the gas will start to accumulate and the central cooling rate will increase. This will increase the accretion rate and lead to the outburst, which in turn will heat the gas and reduce the cooling rate in the center, leading to a self-regulating state.

Additional heating may result from damping of large scale motions caused by entrainment and lifting of the gas surrounding the bubbles. This is the general mechanism proposed by Begelman (2001) and Ruszkowski & Begelman (2002) in their discussion of “effervescent heating”. The widespread spatial distribution of heat in this mechanism can be achieved when the buoyant bubbles rise in the ICM perturbed by preceding bubbles. That is, subsequent bubbles find lower resistance to move in all directions once they encounter underdense regions “drilled” by earlier bubbles. Moreover, when the bubbles move a substantial distance from the cluster center, the lateral spreading is further enhanced as the bubble entropy becomes comparable to the entropy of the ambient medium. Spatial spreading of heat could also be facilitated if the jet or other form of outflows) precesses or if the black hole in the center of the AGN adjusts in response to a change in the orientation of the accretion disk. This could be triggered by a merger with a substructure clump in the cluster or by the oscillatory motion of the AGN around the cluster center of gravity (see e.g. Johnstone et al. 2002).

4. SUMMARY

To summarize, we have analyzed the energy deposition in the cluster due to rising bubbles, sound waves and weak shocks. This was motivated by the recent discovery of such waves in the Perseus cluster by Fabian et al. (2003a) and in the Virgo cluster by Forman et al. (2004). We found that the dissipated energy may be comparable to the cooling rate, thereby significantly affecting the cooling flow or even quenching it altogether. We showed that about 50 per cent of the energy injected by the central source can
be transferred to the ICM. Approximately 40 per cent of the energy injected by the AGN can be converted to heat, assuming Spitzer viscosity. We discussed the wave decay rates and showed that a significant fraction of wave energy is deposited within the cooling radius. The computed decay rates are consistent with linear theory estimates of the damping length. The damped sound waves or weak shocks are still detectable in unsharp-masked X-ray images. Old bubbles become increasingly difficult to detect in the X-ray maps as the contrast between the rising bubbles and the surrounding gas diminishes. However, apart from sound waves and weak shocks in unsharp-masked X-ray maps, the interfaces between the intracluster medium and old bubbles are also clearly visible. This opens up the possibility of detecting fossil bubbles that are difficult to detect in radio emission.

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Fig. 1.— Top row shows the X-ray emissivity maps of the AGN-heated cluster. Snapshots correspond to $3.0 \times 10^7$, $1.15 \times 10^8$, $1.25 \times 10^8$, $1.55 \times 10^8$ and $1.85 \times 10^8$ years, from left to right, respectively. Middle row shows X-ray unsharp masked maps corresponding to X-ray maps. Bottom row shows the map of the viscous dissipation pattern. Whereas the maps in the bottom row show cross-sections through the cluster center that are perpendicular to the line of sight, the first two rows correspond to projections onto the plane of the sky.

Fig. 2.— The ratio of viscous heating to radiative cooling rate as a function of time for a number of concentric shells around the cluster center. The curves that start rising at later times correspond to shells located further away from the center. The heating-to-cooling ratio was calculated in ten shells starting from the first shell at 5 kpc and the remaining shells located in increments of 10 kpc away from the cluster center. Note that the heating rate is comparable to the cooling rate.
Fig. 3.— The ratio of viscous heating to radiative cooling rate as a function of distance from the cluster center for equally-spaced time intervals of $\Delta t = 10^7$ yr until $2 \times 10^8$ yr.

Fig. 4.— The ratio of volume-integrated heating rate (within 100 kpc from the center) to volume-integrated cooling rate as a function of time.
Fig. 5.— The cumulative injected energy $E_{\text{inj}}$ (solid curve), bubble energy $E_{\text{bubb}}$ (dashed curve) and energy transferred to the ambient ICM ($\equiv E_{\text{inj}} - E_{\text{bubb}}$; dotted curve) as a function of time. All plots are in arbitrary units. We only plot data until 60 Myr as for later times the waves start to escape the computational box.

Fig. 6.— The ratio of cumulative transferred energy to the cumulative injected energy (top curve) and the ratio of the cumulative viscously dissipated energy to the cumulative injected energy as a function of time. We only plot data until 60 Myr as for later times the waves start to escape the computational box.
Fig. 7.— The wave energy flux as a function of the distance from the cluster center. The $\sim r^{-2}$ decay profile is shown for comparison. All quantities are in arbitrary units.