Perseus in Sicily: From Black Hole to Cluster Outskirts
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AGN Jets, Bubbles, and Heat Pumps

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Abstract. Radio-mode feedback from relativistic jets is one of the prominent heating mechanisms in clusters of galaxies. We present a long-term evolution of high-resolution MHD simulation of jets interacting with an environment modeled to represent the Perseus cluster. We investigate the thermodynamics of the ICM due to the gas motion triggered by the action of the jets and show that low-entropy gas is lifted efficiently in the wake of the inflating radio lobe. We look into the uplift mechanism and estimate the energy budget and the rate of thermal conduction. The redistribution of entropy suggests that heat conduction can play a more significant role in the thermal evolution of the cluster core in the presence of jets, which act effectively as a *heat pump*, thus heating the ICM more efficiently than jets would by themselves in an isentropic cluster.

Keywords. method: numerical, galaxies: clusters: general, cooling flow, jets, conduction

1. Introduction

The core of galaxy clusters often exhibits strong x-ray emission with short cooling time, which should lead to substantial radiative cooling and the formation of a *cooling flow* (Fabian 1994). The lack of such flows in observations stimulates the study of feedback processes that could counteract the cooling. Mechanical energy deposited by the jets could be one of the important mechanisms regulating the thermal evolution of galaxy clusters (McNamara & Nulsen 2012). X-ray observations of galaxy clusters often show radio-filled cavities that are likely inflated by jets from the supermassive black holes in the central galaxy (see e.g. Birzan *et al.* 2004). In some cases, multiple cavities caused by episodic jet activities are observed. The most detailed observations of this kind include the Perseus Cluster (Fabian *et al.* 2011) and M87 (Forman *et al.* 2007). Churazov *et al.* (2000) show that observed cavities are energetically to offset the cooling in most systems. Subsequent detailed observations support the claim (see e.g. Rafferty *et al.* 2006).

However, the processes through which the energy of AGN jets couples to the ICM are still under debate. Possible mechanisms include turbulence (Zhuravleva *et al.* 2014), sound waves (Fabian *et al.* 2017), mixing (Hillel & Soker 2016), shocks (Fabian *et al.* 2006; Li *et al.* 2017), and internal waves (Zhang *et al.* 2018), among others.

Although most of the discussion about the heating focuses on the direct energy coupling between the AGN output and the ICM, a few authors have pointed out that the removal of the cool gas from the core of the cluster could possibly prevent catastrophic cooling. Pope *et al.* (2010) calculate the amount of gas transported by a rising bubble and conclude that the mass transport by the bubble wake could prevent the core from overcooling. We propose that this uplift mechanism along with heat exchange through conduction could provide the necessary mechanism to extract additional energy from the hot atmosphere of the cluster.

Buoyantly rising bubbles are identified and studied by many works. Churazov *et al.* (2001) conduct hydrodynamic simulations of bubbles to model the radio and x-ray

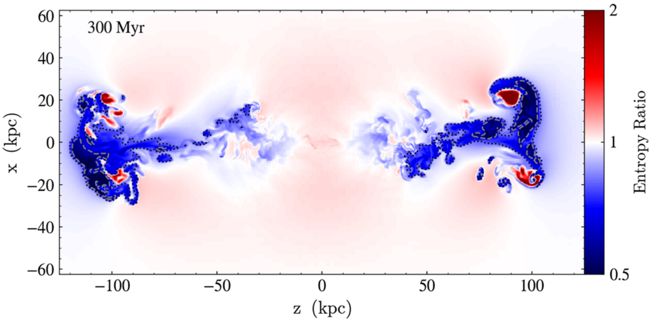

Figure 1. Slice of the simulation showing the entropy of the gas relative to the initial entropy value at the same location. Dotted and dashed contours indicate the ratio of 0.8 and 0.6 respectively.

arms in M87. In a deep *Chandra* observation, Forman *et al.* (2007) detect many filamentary structures that could be associated by independent bubbles in M87. Recently, Gendron-Marsolais *et al.* (2017) report observations of cool x-ray gas rims in NGC 4472 that could be gas lifted by the bubbles. These works all suggest that rising bubbles are prevalent and could bring gas from the core to the outskirt of the galaxy cluster.

In this work, we consider the mechanism that rising bubbles bring the low-entropy gas from the cool core to the hot outskirt of the galaxy cluster where thermal conductions are much more efficient. With this mechanism, the AGN could “heat” the ICM more than its own energy budget would indicate if the energy were directly transferred to heat and that this heating process and is much more gentle than direct heating.

2. The Simulation and Implicatons

Here we summarize the important and relevant information of the simulation and leave the details to a separate paper. We conduct full 5D ideal MHD simulations using `FLASH` (Fryxell *et al.* 2000; Dubey *et al.* 2009) with the unsplit staggered mesh scheme (Lee 2013). In a background environment tuned to match the Perseus Cluster observed by Zhuravleva *et al.* (2015), we set up a nozzle through which energy, momentum, and magnetic fluxes are injected into the grid to model the radio jets. The initial condition is in hydrostatic equilibrium and not magnetized. The jet is active for 10 Myr, during which it outputs at a constant power 10^{45} erg/s. After 10 Myr, the jet ceases and the bubbles continue to rise due to buoyancy. Radiative cooling and thermal conduction are not included in the simulation. We study the long-term impact of this one-time activity of the jets on the thermal state of the galaxy cluster.

2.1. *Low-entropy gas transported by the rising bubble*

First, we investigate the occurrence and the entropy structure of the gas displaced by the AGN. During the active phase of the AGN, only a small amount of gas is displaced by the jet. However, as bubbles rise, they drag a significant amount of gas from the core in the wake of the bubbles. This phenomenon can be seen clearly in the entropy ratio map. In Figure 1, the specific entropy, defined as kT/n^{γ}, of the gas is plotted relative to the entropy profile of the initial condition. Since the entropy is conserved during adiabatic processes, it better indicates the origin of the gas. At the time of this figure, most of the hot gas injected by the jet is mixed with the ICM. Only a small fraction of the hot gas is still visible as a ring surrounded by the lower-entropy gas.

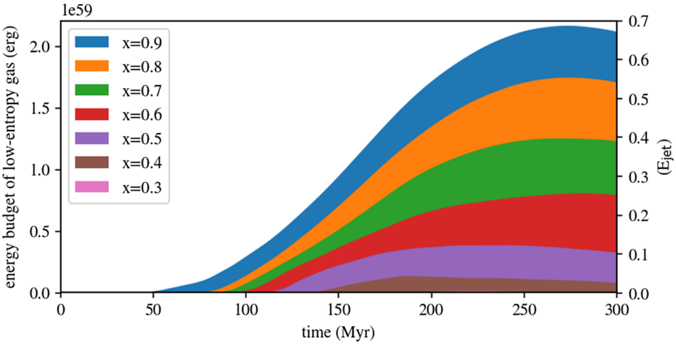

Figure 2. Energy budget of the low-entropy gas. This shows the evolution of the amount of energy needed to bring the low-entropy gas, which is identified by entropy ratio lower than the threshold x, back to the surrounding temperature. The y-axis on the right shows the ratio relative to the total energy injected by the active jet in the first 10 Myr.

2.2. *Energy budget of the low-entropy gas lifted by the rising bubble*

Second, we consider the amount of energy that can be extracted from the hot gas and transferred to the uplifted low-entropy gas by heat conduction. We identify the gas with entropy ratio below a threshold of x in the simulation and estimate the amount of energy needed to bring this gas into thermal equilibrium with its surrounding. This is the amount of energy available for heating low entropy gas through uplift and conduction. Figure 2 shows the evolution of this energy as a function of time with different values of x. The y-axis at the left labels the energy in *erg*, while the y-axis at the right denotes this energy relative to the total energy injected during the active phase of the jet (10 Myr). One can see that the conductive energy budget of the low-entropy gas is comparable to the total energy injected by the jet. It is important to keep in mind that this energy is not from the AGN itself, but from the hot atmosphere at large radii of the clusters. When the gas is brought into thermal contact with the hot reservoir, heat exchange can take place more efficiently. We discuss the rate of the heat exchange next.

2.3. *Heating rates of Spitzer thermal conduction*

Finally, we estimate the rate of thermal conduction between the low-entropy and hot gas. We consider the classic Spitzer conduction in ionized gas (Spitzer 1962, see also Narayan & Medvedev 2001). The Spitzer coefficient can be calculated as

$$\kappa_{\rm Sp} \sim 4 \times 10^{32} \left(\frac{kT}{10\ {\rm keV}}\right)^{5/2} \left(\frac{n}{10^{-3}{\rm cm}^{-3}}\right)^{-1} {\rm cm}^2{\rm s}^{-1}. \tag{2.1}$$

The coefficient has a strong dependence on the temperature. This is why thermal conduction is usually considered too slow to offset the cooling in the cool core of the cluster. However, once the cool gas is transported to large radii and placed in close spatial proximity to hot gas, the high temperature and increased temperature gradient both accelerate the thermal conduction rate. We then calculate the heat flux by $q = nkf_{\rm Sp}\kappa_{\rm Sp}\nabla T$, in which $f_{\rm Sp}$ is the fraction relative to the classic Spitzer conduction rate and depends on the orientation of the magnetic fields. Since we do not include magnetic fields in the initial ICM, it is impossible to include the anisotropic conduction in this analysis. The instantaneous heating and cooling rate due to the conduction is the divergence of the heat flux. We then add the thermal conduction heating/cooling rates and x-ray cooling rate in each cell. The summed values are shown in Figure 3 in entropy and radial bins (left panel) and in entropy bins (right panel).

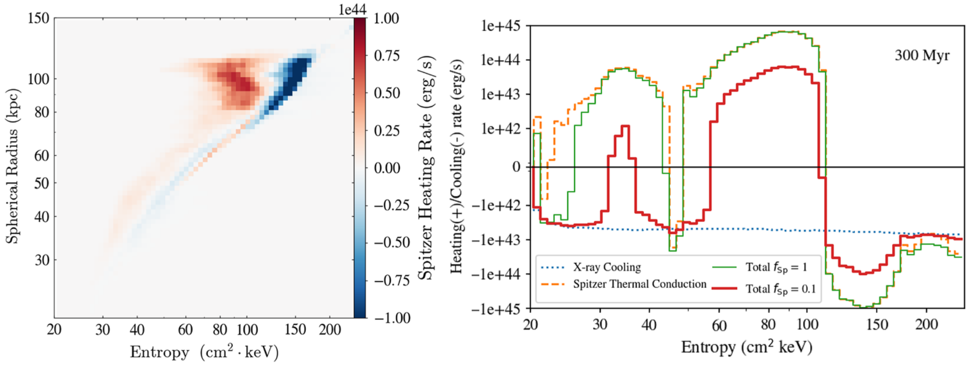

Figure 3. Heating rate histogram at 300 Myr. The total heating and cooling rates are summed in each entropy and radial bins (left panel, $f_{\rm Sp} = 1$) and in entropy bins (right panel) with two $f_{\rm Sp}$ values.

At the same radius, heat is transferred from high-entropy to low-entropy gas. Although the details of the conduction need to be scrutinized, we found that at 0.1 Spitzer value ($f_{\rm Sp} = 0.1$), the thermal conduction will still be able to bring the low-entropy gas to the temperature of the heat reservoir in a short amount of time. The heating rate is also comparable to the power of the jet (10^{45} erg/s) even at 300 Myr.

3. Discussions and Conclusions

We want to emphasize that this is an exploratory work inspired by the long-term evolution of our simplified numerical experiment. To investigate this heat-pump mechanism rigorously, we will need to re-designed the simulation to include effects like radiative cooling and anisotropy thermal conduction. However, our preliminary analysis indicates that this is a promising process that can provide another avenue in the already hotly debated cooling flow problem.

We consider the idea that the radio AGN could act as a "*heat pump*" by inflating buoyant bubbles that lift the low-entropy gas from the core of the clusters into thermal contact with the hot atmosphere. In this mechanism, the total available energy gained by the cluster core to offset the radiative cooling is not simply limited by the total energy output of the AGN, but also the heat transferred from the hot gas at large radii of the cluster to the uplifted low-entropy gas. Our analysis implies that a 10-Myr active jet could still affect the thermal states of the clusters after 300 Myr. This mechanism has the advantage that bursty AGN activity is transformed into a more gentle and longer-lasting heating process.

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