The Role of Turbulence in AGN Self-Regulation in Galaxy Clusters

Evan Scannapieco* and Marcus Brüggen†

*School of Earth and Space Exploration, Arizona State University, P.O. Box 871404, Tempe, AZ, 85287-1404, USA
†Jacobs University Bremen, P.O. Box 750 561, 28725 Bremen, Germany

Abstract.

Cool cores of galaxy clusters are thought to be heated by low-power active galactic nuclei (AGN), whose accretion is regulated by feedback. However, the interaction between the hot gas ejected by the AGN and the ambient intracluster medium is extremely difficult to simulate, as it involves a wide range of spatial scales and gas that is Rayleigh-Taylor (RT) unstable. Here we use a subgrid model for RT-driven turbulence to overcome these problems and present the first observationally-consistent hydrodynamical simulations of AGN self-regulation in galaxy clusters. For a wide range of parameter choices the cluster in our three-dimensional simulations regulates itself for at least several 10^9 years. Heating balances cooling through a string of outbreaks with a typical recurrence time of ≈ 80 Myrs, a timescale that depends only on the global cluster properties.

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INTRODUCTION

Many galaxy clusters have strong peaks in their X-ray surface brightness distributions, indicating that their central gas is cooling rapidly. Yet spectra of such cool-core clusters show that this gas fails to cool below ≈ 1 keV [1, 2, 3], which means that radiative cooling must be balanced by an unknown energy source. Currently, the most successful model for achieving this balance relies on heating by outflows from a central active galactic nucleus (AGN) [4, 5]. Galaxies near the centers of groups and clusters show a boosted likelihood of hosting AGN-driven jets [6]. The energies from such jets are comparable to those needed to balance cooling [7], and they increase in proportion to the cooling luminosity as expected in an operational feedback loop [2, 8].

However, the full simulation of this feedback cycle remains elusive. Direct simulation of a galaxy cluster from the Mpc scale down to the parsec scale at which mass accretes onto the central supermassive black hole is still out of reach even for the latest generation of adaptive-mesh refinement (AMR) codes. Hence, in most hydrodynamical simulations of AGN feedback, the energy input is set by hand, rather than computed from the conditions surrounding the central galaxy. In fact only [9], [10], and [11] attempted to simulate self-regulated accretion, and none of these studies was able to reproduce the observed properties of cool-core clusters.

The biggest obstacle to these simulations is that it is unclear how the AGN mechanical power is deposited as thermal energy throughout the cluster. Details of the flow depend on the unknown viscosity of the intracluster medium (ICM), the role of magnetic fields,
and the properties of ICM turbulence – which mixes material on scales unresolved by current simulations. Here we show how tracking subgrid turbulence provides the missing piece necessary to construct full numerical simulations of AGN self-regulation in cool-core clusters. Furthermore, with no fine tuning, such simulations naturally explain both the mechanical power of the AGN and their duty cycles.

**METHOD**

The simulations were performed with FLASH version 3.0, a multidimensional AMR hydrodynamics code. While the direct simulation of turbulence is extremely computationally-expensive and dependent on resolution [12], its behavior can be accurately approximated with a subgrid model. In [13] we showed that AGN jets in the ICM are disrupted into resolution-dependent pockets of underdense gas in pure-hydro simulations, but proper modeling of subgrid turbulence [14] shows that this a poor approximation to a turbulent cascade that continues far beyond current resolution limits.

The simulations presented here were also carried out using this subgrid turbulence model, and for our overall cluster profile, we adopted a model [15] that reproduces the properties of the Perseus cluster. We implemented radiative cooling in the optically-thin limit throughout the simulation, and the energy input from AGN was calculated from the instantaneous conditions near the centre of the cluster. In particular, we considered a model in which a fixed fraction of the gas within the central 3 kpc of the cluster accretes onto the central supermassive black hole within a cooling time, and a fixed fraction of the rest mass energy of this accreted gas is returned to the ICM by increasing the temperature within two hot spots, located 10 kpc above and below the central AGN. Further details of our simulations are given in [16].

**RESULTS**

As a control case, we first present the results of a model without subgrid turbulence (labeled 5N-10), whose evolution is summarized in the top left panel in Fig. 1. In this case the AGN jets do not couple to the central region. Instead, cool gas accumulates in the center, and this cooling eventually leads to a drastic AGN outburst. However even this extreme heating does not stop the flow of infalling gas. Instead cooling increases catastrophically and we are forced to stop the simulation at 480 Myrs.

On the other hand, when the subgrid turbulence model is switched on, as in run 5D-10, the jets couple effectively to the central region. Turbulence mixes in hot material near the center of the cluster, heating the cool inflowing intracluster gas and stopping the AGN outburst. Thus instead of cooling catastrophically, the overall radial temperature and density profile of the cluster remains extremely stable over the course of the simulation, even though substantial cooling continues at all times.

Despite this overall stability, the center of the cluster executes a series of oscillations as indicated in Fig. 1. After each outburst of AGN activity, turbulence decays away at the eddy turn-over time scale, and mixing near the cluster center becomes progressively less efficient. This leads to an increased level of accretion as more and more cold gas...
FIGURE 1. Left panels: Jet power and integrated cooling rates for a run without subgrid turbulence (top left), our fiducial run with subgrid turbulence (top right), and two runs with subgrid turbulence and different hot-spot sizes (bottom left and bottom right). The solid blue lines show the total cooling rate in the simulation volume, the dashed blue lines show the cooling rate in the central 100 kpc, and the red lines show the AGN energy input. The lines for the run without subgrid turbulence stop abruptly at about 450 million years because catastrophic cooling in the center halted the simulation. Right panel: Volume rendering of the temperature in our fiducial run at $t = 630$ Myrs. The blue ring shows the cool gas accreting onto the center; the red and yellow blobs represent the hot gas ejected by the AGN. On the left side one can see an older bubble from an earlier outburst.

makes its way onto the AGN. The result is a new burst of AGN activity, which drives a jet on time scales of the order of a sound crossing time. The RT-unstable jet leads to a rise in turbulent mixing, which quickly quenches accretion when the turbulent length scale grows to be of the order of the scale of the accretion flow. At this point the AGN remains relatively quiescent until the turbulence decays away again, repeating the cycle. This interaction of the AGN-heated regions with the cool inflowing gas is also illustrated in the volume-rendered image shown in the right panel of Fig. 1.

It is important to point out that we did not tweak the parameters of the subgrid model to achieve this self-regulating cycle. Note also that the time scale for the cycle is not the sound crossing time for the central region, which is of the order of 10 Myrs. Instead the period between the episodes of AGN fueling is determined by the time it takes for turbulence to decay after it has mixed the gas in the cluster center. This is given by

$$t_{\text{duty}} \approx l/v_{\text{turb}},$$

(1)

where $l$ is the distance between the accretion region of the AGN and hot spots and $v_{\text{turb}}$ is a typical the turbulent velocity, which we assume grows in a dynamical time given by $v_{\text{turb}} \approx gt \approx gl/c_s$, where $c_s$ is the sound speed. Because the cluster is in hydrostatic balance, the gravitational acceleration can be written as $g = c_s^2 \frac{1}{\rho} \frac{d\rho}{dr} \equiv c_s^2/r_0$. This leads to the turbulent velocity $v_{\text{turb}} = gl/c_s \approx c_s l/r_0$, and thus

$$t_{\text{duty}} \approx \frac{r_0}{c_s}.$$
This means that the size of the hot spots does not enter the expression for the duty cycle as would be expected in a cycle regulated by laminar flow. It is the properties of the cluster itself, rather than the jet physics of the central AGN that are setting the recurrence time of the jets. For the cluster simulated here, the central sound speed is around 700 km/s and the scale height of the cluster is around 60 kpc, so the duty cycle is 60 kpc/700 km/s ≈ 80 Myr regardless of other parameters.

To test this hypothesis we have varied the geometry of the injection region, leading to the heating and cooling evolution shown in the lower panels in the left of Fig. 1. The time between two subsequent outbursts for runs D5-8 and D5-12, in which the hot spots are placed at 8 and 12 kpc from the center respectively, is roughly 80 Myrs, just as in the fiducial case. Furthermore this timescale is consistent with that measured by a number of observational methods [17, 18, 19, 20]. Such cycles are also seen in a sample of nearby elliptical galaxies [21], and it will be interesting to compare our simulations of turbulent self-regulating AGN to such measurements in the near future.

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