Cluster magnetic fields from active galactic nuclei

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Abstract. Active galactic nuclei (AGN) found at the centers of clusters of galaxies are a possible source for weak cluster-wide magnetic fields. To evaluate this scenario, we present 3D adaptive mesh refinement MHD simulations of a cool-core cluster that include injection of kinetic, thermal, and magnetic energy via an AGN-powered jet. Using the MHD solver in FLASH 2, we compare several sub-resolution approaches that link the estimated accretion rate as measured on the simulation mesh to the accretion rate onto the central black hole and the resulting feedback. We examine the effects of magnetized outflows on the accretion history of the black hole and discuss the ability of these models to magnetize the cluster medium.

Keywords: galaxies: clusters, cooling flows, MHD, active galactic nuclei, methods: numerical

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INTRODUCTION

Faraday rotation measures of galaxy clusters suggest they contain magnetic fields with average strengths of \( \sim 1 \, \mu \text{G} \) (e.g., [1]), but the origin of these fields is unknown. Possible seed fields, such as those generated by the Biermann battery mechanism, require amplification [2]. Accretion disks around active galactic nuclei (AGN) are a promising candidate amplification source, since AGN-launched jets require magnetic fields and the energetics of AGN-blown bubbles suggest that AGN can amplify the seed fields to the observed strengths.

We would like to directly test this scenario in simulation, but since AGN accretion disks are typically smaller then \( \sim 100 \, \text{AU} \), and cosmological simulations have resolutions on the order of \( \sim 1 \, \text{kpc} \), we must include the amplification and jet launching as a subgrid model. We investigate two commonly-used AGN feedback models: one based on jets [3], the other on already-inflated bubbles [4]. We link the feedback energies of these models to the strength of an injected magnetic field. We inject magnetic fields with the form described by [5], in which the field has both toroidal and poloidal components.

ANALYTICAL AND NUMERICAL APPROACH

We assume Bondi accretion:

\[
\dot{M}_{\text{Bondi}} = 4\pi G^2 m_{\text{BH}}^2 \rho / c_s^3,
\]  

(1)
where the sound speed $c_s$ and the density $\rho$ are measured on the simulation mesh, and $m_{BH}$ is the black hole mass. Following [4], to compensate for under-resolving the actual accretion disk, we assume a constant multiple of the Bondi rate:

$$\dot{M} = \alpha \dot{M}_{\text{Bondi}}$$

(2)

with $\alpha = 100$.

We follow [3] for modeling jet-based feedback where the energy injection rate is

$$\dot{E} = \epsilon_F \dot{M} c^2 (1 - 1/M_{\text{load}}) |\Psi|.$$  

(3)

Similarly, the momentum injection rate is $\dot{P} = \sqrt{2 \epsilon_F \dot{M} c} \Psi$, and the mass injection rate is $\dot{M}_{\text{inj}} = M_{\text{load}} \dot{M} |\Psi|$.

The window function $\Psi$, which provides a mapping onto the mesh, is

$$\Psi(x) = \frac{1}{2\pi r_{ej}} \exp \left( -\frac{x^2 + y^2}{2 r_{ej}^2} \right) \frac{z}{h_{ej}}.$$  

(4)

We cut off injection at $z = h_{ej}$ and $r = 2.6 r_{ej}$. In the above, $c$ is the speed of light, and we will define the injection region through $r_{ej} = 3.2$ kpc and $h_{ej} = 2.5$ kpc. The injection region is oriented along the z-axis. We assume a jet mass loading factor of $M_{\text{load}} = 100$ and feedback efficiency of $\epsilon_F = 0.1$.

For bubble injection, as in [4], we have only thermal energy injection:

$$\dot{E} = \epsilon_F \epsilon_M \dot{M} c^2,$$

(5)

where $\epsilon_F$ is the same as above and $\epsilon_M = 1.0$. We distribute this energy uniformly in a sphere with radius determined by

$$R_{\text{bub}} = R_0 \left( \frac{\dot{E} dt \rho_0}{E_0 \rho} \right)^{1/5},$$

(6)

where we define the scalings by $R_0 = 43$ kpc, $E_0 = 10^{60}$ erg, $\rho_0 = 10^6 M_\odot \text{kpc}^{-3}$, and $dt$ is the timestep. These scalings ensure that a bubble in a typical cluster environment will have a realistic size. The bubbles are always centered on the black hole, and we only form bubbles when the black hole has increased its mass since the previous bubble formation by $\Delta M_{\text{BH}}/M_{\text{BH}} > 0.001$.

The injected magnetic field takes the form

$$B_r(r',z') = 2B_0 z' r' \exp \left( -r'^2 - z'^2 \right)$$

(7)

$$B_z(r',z') = 2B_0 \left( 1 - r'^2 \right) \exp \left( -r'^2 - z'^2 \right)$$

(8)

$$B_\phi(r',z') = B_0 \alpha_B r' \exp \left( -r'^2 - z'^2 \right),$$

(9)

where $r' = \sqrt{x^2 + y^2}/r_0$ and $z' = z/r_0$. Here, $r_0$ is $1/2R_{\text{bub}}$ for bubbles and $1/2R_{ej}$ for jets, and $\alpha_B$ is the ratio of of polodial to toroidal flux. We choose $\alpha_B = \sqrt{10}$ for an
initially relaxed field, as suggested by [5]. We determine the scale $B_0$ by giving half of the available feedback energy to the magnetic field.

We performed three-dimensional simulations with an isolated cluster profile in a 2048 kpc box using FLASH 2.5 [6], an adaptive mesh refinement (AMR) code. Both the jet and bubbles runs used a maximum resolution of 1.0 kpc within the central 50 kpc region. The AGN began as a $10^7 M_\odot$ black hole in the center of an NFW ([7]) gravitational potential. The cluster had a concentration of 6.5, scaling radius of 165 kpc, total mass of $10^{14} h^{-1} M_\odot$, and gas fraction of 0.12. We included cooling from [8] assuming 1/3 solar metallicity. We allowed the cluster to relax for $\sim$ 1 Gyr before activating cooling and feedback.

**RESULTS**

Figure 1 shows the accretion history of the black hole with both magnetized and unmagnetized jet- and bubble-based feedback until the cooling catastrophe occurs. We find that magnetizing bubbles does not greatly alter the accretion rate relative to unmagnetized injections, since bubbles occur infrequently. However, magnetizing jets greatly reduces the accretion rate. Here, the combination of an axial jet and a toroidal magnetic field prevents gas from accreting.

We show the volume magnetized in Figure 2. Both jets and bubbles are able to weakly magnetize large volumes. These fields may be further amplified in realistic clusters by turbulence and merger shocks. However, significant ($>1 \mu G$) fields do not penetrate far from the cluster core. Finally, only the jet is able to produce greater than 20 $\mu G$ fields, but these quickly dissipate. The outflows begin to greatly enhance the magnetization of the cluster at the onset of the cooling catastrophe.

With the parameter values used, we find that these feedback mechanisms do not provide enough heating to prevent the cooling catastrophe. We are investigating the new
FIGURE 2. Magnetized volume for various thresholds. The y-axis is the cube root of the total volume that lies above each threshold.

MHD solver in FLASH 3 ([9]) to determine whether or not this is a numerical effect.

The evolution of our injected magnetic fields resembles that of [5], but they consider only pure magnetic injection from a single source with fixed energy input. Our energy input depends on the accretion rate, and we find much less available energy than the value they assume ($\sim 10^{60}$ ergs).

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