Cluster magnetic fields from active galactic nuclei

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Introduction

While active galactic nuclei (AGN) are a strong candidate for the source of galaxy cluster-wide magnetic fields, it is not clear how to include sub-grid models of AGN-based magnetic injection into cosmological simulations. Accreting material powers the AGN on scales below the highest resolution limits of cosmological simulations. Injection takes the form of powerful jets which occasionally inflate large bubbles. These bubbles then rise, dissipate, and mix with the surrounding intracluster medium.

We investigate two commonly-used AGN feedback models: one based on jets, the other on already-inflated bubbles. We link the feedback energies of these models to the strength of an injected magnetic field. Using isolated cluster simulations, we evaluate these models to determine their ability to reproduce realistic magnetic structures in clusters and their appropriateness for inclusion in larger simulations. We also study the ability of these models to substantially magnetize an isolated and initially unmagnetized cluster.

Accretion Model

We will assume Bondi accretion

$$\dot{M}_{Bondi} = 4\pi G^2 m_{BH}^2 \rho / c_s^3$$

where the sound speed c_s and density ρ are measured on the mesh, and m_{BH} is the central black hole mass. Even at our highest resolution, we will under-resolve the actual accretion disk, and hence underestimate the realistic accretion rate. Hence we will assume a constant multiple of the Bondi rate:

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

with α=350.

Feedback Models

Jets *(e.g., Cattaneo et al. 2007)*

- Centered on AGN, cylindrical injection region
- Injects mass and thermal & kinetic energy
- Continuous feedback

$$\dot{E} = \varepsilon_F \dot{M} c^2 (1 - 1/M_{Load}) \cdot \Psi$$

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

r_{ej} = 3.2 kpc*, h_{ej} = 2.5kpc, M_{load}=100, ε_F=0.1

Bubbles *(e.g., Sijacki et al. 2008)*

- Placed randomly near AGN, spherical injection region
- Injects thermal energy only
- Feedback only if ΔM_{BH}>0.001

$$\dot{E} = \varepsilon_F \varepsilon_M \dot{M} c^2$$

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

R_0 = 43 kpc, $E_0 = 10^{60}$ erg, $\rho_0 = 10^6 M_\odot kpc^{-3}$, ε_F=0.1, ε_M=1.0

*1 kpc = 3.09×10^{21} cm

Magnetic Field Injection

We assume a poloidal and toroidal configuration (Li et al. 2006):

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

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

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

$$r' = \sqrt{x^2 + y^2} / r_0 \qquad z' = z / r_0$$

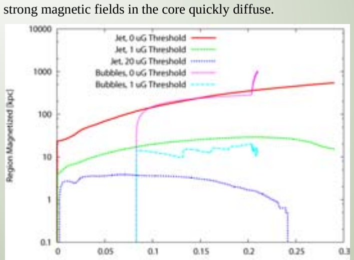
r_0 is the jet or bubble radius and α is the ratio of poloidal to toroidal flux. The total magnetic energy is a fixed fraction of the injected thermal energy. We will assume that half the total feedback energy goes to the magnetic field.

Simulations

We performed three-dimensional simulations with an isolated cluster profile in a 2048 kpc box using FLASH 2 (Fryxell et al. 2000). The jet run used a maximum resolution of 0.5 kpc in the central 40 kpc region, while the bubbles were resolved to 4 kpc in the central 200 kpc. The AGN source is a $10^7 M_\odot$ black hole in the center of an NFW gravitational profile with concentration of 6.5 and scaling radius of 165 kpc. We include cooling from Sutherland & Dopita (1993) assuming 1/3 solar metallicity. We allowed a $10^{14} M_\odot$ cluster to relax for ~1 Gyr before activating cooling and feedback.

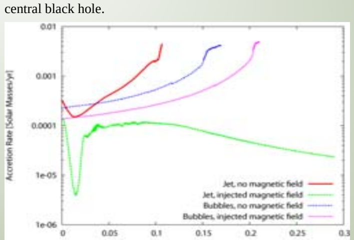
Magnetized Volume

Below are the volumes magnetized by both jets and bubbles. Both jets and bubbles weakly magnetize large volumes, but strong magnetic fields in the core quickly diffuse.



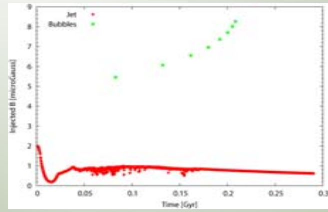
Magnetism and Accretion

We measured the accretion rates for both magnetized and unmagnetized outflows. The magnetized jets prevent the cooling catastrophe and hence the rapid accretion onto the central black hole.



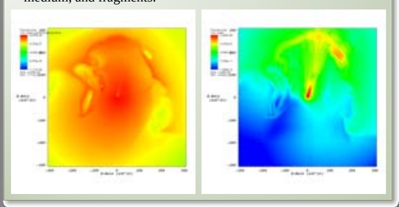
Injected Magnetic Strength

Jets produce a continuous source of ~1 μG fields in a smaller volume, while a few discrete bubble events place 5-10 μG fields over a larger area of the central core.



Magnetized Outflows

Shown below are snapshots of density (left) and mean magnetic field (right) at 200 Myr for the magnetized jet. The jet inflates a bubbles which detaches, rises into the cluster medium, and fragments.



Conclusions

Jets and bubbles appear to weakly magnetize a cluster and generate μG-scale fields in the cores. These fields may be further amplified by turbulence and merger events. However, the development of the cooling catastrophe prevents the formation of additional bubbles. While magnetized jets prevent the catastrophe, they do not reach significant strengths very rapidly.

We are currently studying additional accretion models and multiple resolutions. We will also consider "two-mode feedback", in which case the feedback mode changes depending on the accretion rate.

The most realistic of these candidate models will be integrated into a full cosmological simulation.

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