AGN jets do not prevent the suppression of conduction by the heat buoyancy instability in simulated galaxy clusters

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ABSTRACT

Centres of galaxy clusters must be efficiently reheated to avoid a cooling catastrophe. One potential reheating mechanism is anisotropic thermal conduction, which could transport thermal energy from intermediate radii to the cluster centre. However, if fields are not re-randomised, anisotropic thermal conduction drives the heat buoyancy instability (HBI) which reorients magnetic field lines and shuts off radial heat fluxes. We revisit the efficiency of thermal conduction under the influence of spin-driven active galactic nuclei (AGN) jets in idealised magneto-hydrodynamical simulations with anisotropic thermal conduction. Despite the black hole spin’s ability to regularly re-orientate the jet so that the jet-induced turbulence is driven in a quasi-isotropic fashion, the HBI remains efficient outside the central 50 kpc of the cluster, where the reservoir of heat is the largest. As a result, conduction plays no significant role in regulating the cooling of the intracluster medium if central active galactic nuclei are the sole source of turbulence. Whistler-wave driven saturation of thermal conduction reduces the magnitude of the HBI but does not prevent it.

Key words. galaxies: clusters: intracluster medium – methods: numerical – galaxies: magnetic fields – instabilities – galaxies: jets

1. Introduction

The hot intracluster medium (ICM) is a substantial thermal energy reservoir. If this energy can be efficiently transported to the cluster centre via thermal conduction, it could offset some of the centre’s radiative cooling (Fabian 1994; Binney & Tabor 1995), and thereby contribute to the long-term thermal stability of the cluster (Tucker & Rosner 1983; Santos 2000; Narayan & Medvedev 2001; Ruszkowski & Begelman 2002).

The conductive heat flux $F_{\text{cond}}$ takes the form (Spitzer & Härm 1953)

$$F_{\text{cond}} = -\kappa e \hat{b} \cdot \nabla T_e$$

where $\kappa$ is the Spitzer conductivity for electrons, $\hat{b}$ is the unit vector along the magnetic field and $T_e$ is the electron temperature. Assuming a predominantly radial temperature gradient, as seen in galaxy clusters,

$$F_{\text{cond}} = -\kappa f_c \frac{\partial T_e(r)}{\partial r}$$

where $f_c$ parameterises the effective strength of the conductive heating in comparison to the Spitzer value. As thermal conductivity is high along magnetic field lines but effectively zero across them (Spitzer & Härm 1953), the effective efficiency of thermal conduction, $f_c$, depends strongly on magnetic field morphology. It is equal to $f_c = b_z^2$, where $b_z = b \cdot \hat{r}$ is the magnetic field unit vector in the radial direction. A tangled magnetic field has $f_c = 1/3$, as the magnetic field is equally likely to be oriented in each of the three dimensions, whereas a radial field has $f_c = 1$. The required values of $f_c$ to offset radiative cooling depends on the cluster (Jacob & Pfrommer 2017).

In the presence of thermal conduction, the Heat-Buoyancy instability (HBI) (Quataert 2008; Parrish et al. 2009) can reorient the cluster magnetic field. It acts when the temperature increases with height ($\mathbf{g} \cdot \nabla T_e < 0$, where $\mathbf{g}$ is the gravitational acceleration). Left unchecked, the HBI will rearrange magnetic fields in galaxy cluster centres to a tangential configuration, suppressing conductive heat fluxes (Parrish et al. 2009; Bogdanović et al. 2009). Turbulence can counteract the HBI and re-randomise the magnetic field (Ruszkowski & Oh 2010).

Thermal conduction has the potential to reduce cluster cooling flows (Ruszkowski et al. 2011) and the total energy required for Active Galactic Nuclei (AGN) to regulate cluster cooling flows (Kannan et al. 2016; Barnes et al. 2019), but its efficiency depends on the efficiency of the HBI. This, in turn, depends on the relative magnitude of turbulent and buoyant timescales (McCourt et al. 2011). Volume-filling turbulence of 50 – 100 kms$^{-1}$ can suppress the HBI and allow for $f_c = 0.5$ (Ruszkowski & Oh 2010). This is a level of turbulence that can be delivered by a simplified AGN-based turbulence model (Parrish et al. 2012), but more recent simulations employing fixed direction AGN jets found that the HBI remains active outside the jet cone (Karen Yang & Reynolds 2016; Su et al. 2019), which limits thermal conduction.

If AGN are only able to re-randomise magnetic fields around the jet cone, the jet direction is a key variable that determines the ability of the central AGN to prevent the HBI. In this paper, we revisit whether an AGN jet can offset the HBI and allow for efficient thermal conduction using a more self-consistent treatment of jet direction. The paper is structured as follows: the simula-

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tion setup is laid out in Section 2, insights on the evolution of the HBI are presented in Section 3.1, the cooling flow is analysed in Section 3.2 and conclusions are summarised in Section 4.

2. Simulations

All simulations presented in this paper are part of the same suite as those presented in Beckmann et al. (2022). We briefly summarise the setup here but refer the reader to Beckmann et al. (2022) for further details.

In this paper we present a set of magneto-hydrodynamical (MHD) simulations of isolated galaxy clusters with and without thermal conduction. The cluster simulations are run with the adaptive mesh refinement code RAMSES (Teyssier 2002) that approximates the solution in the unsaturated and saturated mean free path of electrons $\lambda_e$. The magnetic field is modelled as a fixed background potential (Andreon et al. 2017). The gas is initialised in hydrostatic equilibrium and dark matter is modelled as a fixed background potential (Dubois & Commerçon 2016), including the anisotropic conductive heat flux $\mathbf{F}_{\text{cond}} = -\kappa_e \hat{\mathbf{b}} \cdot \nabla T_e$ (see Eq. (1)). This includes the Spitzer conductivity,

$$\kappa_e = f_{\text{sat}} \kappa_{\text{op}} = f_{\text{sat}} n_e k_0 D_{\text{cond}}$$

where $n_e$ is the electron number density, $k_0$ the Boltzmann constant and $D_{\text{cond}}$ the thermal diffusivity. The conductive flux saturates once the characteristic scale length of the gradient of temperature $\ell_T = T_e / \nabla T_e$ is comparable or shorter than the mean free path of electrons $\lambda_e$ (Cowie & McKee 1977). We follow Sarazin (1986) and introduce an effective conductivity that approximates the solution in the unsaturated and saturated regime by

$$f_{\text{sat}} = \frac{1}{1 + 4.2 \lambda_e / \ell_T_e}.$$  \hspace{1cm} (3)

When taken into account, the whistler instability (e.g. Roberg-Clark et al. 2016; Komarov et al. 2018) can reduce the saturation coefficient to

$$f_{\text{sat,whist}} = \frac{1}{1 + (4.2 + \beta/3) \lambda_e / \ell_T_e}$$  \hspace{1cm} (5)

for high plasma-$\beta$ pressures. Our simulations use Eq. (4), except for AGN_whistler, which uses Eq. (5) (See Table 1).

The induction equation is solved with constrained transverse transport (Teyssier et al. 2006), which guarantees $\nabla \cdot \mathbf{B} = 0$ at machine precision. The MHD system equations are solved using the MUSCL-Hancock scheme (Fromang et al. 2006; Dubois & Commerçon 2016; Dashyan & Dubois 2020) using a minmod total variation diminishing scheme, and the HLLD Riemann solver (Miyoshi & Kusano 2005). The flux for the anisotropic thermal conduction is solved with an implicit method (Dubois & Commerçon 2016; Dashyan & Dubois 2020) using a minmod slope limiter on the transverse component of the face-oriented flux (Sharma et al. 2007).

Clusters are initialised with cored NFW profiles (Navarro et al. 1997) (gas and dark matter) with a total mass of $8 \times 10^{14} M_\odot$, a core radius of 13 kpc, a concentration parameter of $c_{\text{200}} = 4.41$ (Maccio et al. 2007) and a gas fraction of 0.103 (Andreon et al. 2017). The gas is initialised in hydrostatic equilibrium and dark matter is modelled as a fixed background potential. A black hole sink particle of mass $1.65 \times 10^{10} M_\odot$ (Phipps et al. 2019) is placed at the centre of the box. The magnetic field is initialised in a tangled configuration on a characteristic length scale of 10 kpc. It is scaled with the initial gas density profile $\rho(r)$ as $B(r) = B_0(\rho(r)/\rho_0)^{1/3}$ where $B_0 = 20 \mu G$ and $\rho_0$ is the central density of the cluster.

Radiative cooling is calculated according to Sutherland & Dopita (1993) for temperatures above $T > 10^4 K$, with values extended below $10^4 K$ using Rosen & Bregman (1995). Metallicity is treated as a passive scalar advected with the flow. It is initialised as $Z = \min \left(0.45, \max \left(0.22, 0.15 \left(\frac{T}{200} \right)^{-0.28}\right)\right)$ using limits from Leccardi & Molendi (2008) and Urban et al. (2017). Star formation proceeds in cells with hydrogen number density $n_h > 0.1 \text{ H cm}^{-3}$ and temperature $T < 10^5 K$, at a stellar mass resolution of $m_* = 3.89 \times 10^4 M_\odot$. Stellar feedback includes type II supernovae only, using the energy-momentum model of Kimm et al. (2015) using an efficiency of $\eta_{\text{SN}} = 0.2$ and a metal yield of 0.1.

The black hole accretes according to the Bondi-Hoyle-Lyttleton accretion rate, limited to a maximum Eddington fraction of 0.01 (Dubois et al. 2012). The black hole spin is initialised at zero (spin parameter $a = 0$), and evolves throughout the simulation assuming a magnetically arrested disc McKinney et al. (2012). A fraction $\epsilon_{\text{EAD}(a)}$ of the accreted mass is returned as AGN bipolar kinetic outflows aligned with the black hole spin axis, using the implementation from Dubois et al. (2014, 2021). As this spin vector naturally evolves under the influence of chaotic cold accretion on the black hole (Gaspari et al. 2013), there is no need to add further jet precession (Beckmann et al. 2019).

In AGN_cr, a fraction $f_{\text{cr}} = 0.1$ of the jet energy is injected into cosmic rays (see Beckmann et al. 2022, for details). During AGN feedback, a passive scalar is injected at the jet base which is used for refinement only. It decays with a decay time of 10 Myr.

The cluster profile is truncated at the virial radius ($r_{200} = 1.9\, \text{ Mpc}$), and embedded in a box of size 8.7 Mpc. Simulations were performed on a root grid of $64^3$, adaptively refined to a maximum resolution of $\Delta x = 531$ pc if any of the following criteria are met: 1) The gas mass in a cell exceeds $[27089, 8713, 4098, 1621, 461, 152, 59, 12, 12] \times 1.47 \times 10^6 M_\odot$ (levels 6 to 14). 2) The cell is located within $4\Delta x$ of the black hole. 3) The cell density of the passive scalar injected by the jet exceeds $\rho_{\text{scalar}} / \rho_{\text{gas}} > 10^{-4}$ and its gradient exceeds 10%.

Simulation parameters are summarised in Table 1.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>AGN conduction</th>
<th>$f_e$</th>
<th>Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>noAGN_nocond</td>
<td>no</td>
<td>no</td>
<td>-</td>
</tr>
<tr>
<td>noAGN_cond</td>
<td>no</td>
<td>anisotropic</td>
<td>$f_{\text{sat}}$</td>
</tr>
<tr>
<td>AGN_nocond</td>
<td>jet</td>
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<td>-</td>
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<tr>
<td>AGN_cond</td>
<td>jet</td>
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<td>$f_{\text{sat}}$</td>
</tr>
<tr>
<td>AGN_third</td>
<td>jet</td>
<td>anisotropic</td>
<td>$1/3$</td>
</tr>
<tr>
<td>AGN_iso</td>
<td>jet</td>
<td>isotropic</td>
<td>$1$</td>
</tr>
<tr>
<td>AGN_whistler</td>
<td>jet</td>
<td>anisotropic</td>
<td>$f_{\text{sat,whist}}$</td>
</tr>
<tr>
<td>AGN_cr*</td>
<td>$f_e = 0.1$</td>
<td>anisotropic</td>
<td>$f_{\text{whist}}$</td>
</tr>
</tbody>
</table>

Table 1. Simulation parameters. $f_e$ is the fraction of Spitzer conductivity used in the conductive heating rate of the simulation. *Simulation AGN_cr has cosmic rays, and is identical to CRc_dsh_weak from Beckmann et al. (2022).

3. Results

3.1. AGN jets and the HBI

As can be seen in the magnetic field morphology shown in Fig. 1, the presence of a self-regulating AGN only affects the magnetic field orientation in the central 50 kpc of the cluster. Without AGN, the central magnetic fields tend to be radial, while with AGN they are effectively randomised by the jet and resulting
Fig. 1. Line integral convolution of the magnetic field, in the plane of the image. Colourmaps are for visualisation only. The black hole is marked as a black cross, and the instantaneous jet direction by an orange line. The white circle have radii of 50 (dashed) and 100 (solid) kpc respectively. In the presence of conduction, the HBI re-orient the magnetic field in a tangential configuration outside the central region.
turbulence. At larger radii, conduction drives the HBI to tangentialise the magnetic field while in the absence of conduction, the magnetic field remains tangled (without an AGN).

This evolution is shown quantitatively in Fig. 2 in the form of volume-weighted average radial profiles of the radial component of the magnetic field unit vector, \( < b_r^2 > \), for concentric radial shells. For all simulations, the initial conditions (dotted black line) are consistent with a tangled magnetic field (\(< b_r^2 > = 1/3\)). From there, the evolution diverges: without conduction, \(< b_r^2 >\) increases (noAGN_nocond and AGN_nocond). With conduction (noAGN_cond and AGN_cond, AGN_whistler and AGN_cr), \(< b_r^2 >\) decreases out to the radius where the cluster temperature profile turns over (grey vertical line, \( r = 358 \) kpc at \( t = 0 \) Gyr), i.e. within the region where the HBI can act.

Low \(< b_r^2 >\) is a clear sign of the HBI in action, which in our simulation continues to decrease \(< b_r^2 >\) over the full 3 Gyr of evolution. This is the fact that, unlike in Karen Yang & Reynolds (2016) and Su et al. (2019), our jets sweep out a significant volume of the cluster centre over the 3 Gyr evolution studied here. This can be seen in Fig. 3, which shows the direction of jet axis as a function of time. While this more isotropic injection of turbulence is effective at counteracting the HBI within the cluster centre, the limited extent of the jets means values of \(< b_r^2 >\) still fall as low as 0.1 by \( r = 100 \) kpc, which produces an effective barrier to heat fluxes to the cluster centre. In our model, the jet has a comparatively low average spin value of about \( a = 0.1 \) (see Beckmann et al. 2019, for a discussion of the BH spin evolution), which means the spin direction is more easily adjusted as for a faster spinning BH. It is possible that a jet with a more fixed direction would be able to inject turbulence to larger radii, but this would come at the cost of affecting a smaller fraction of the core volume. We will leave an investigation into the impact of the jet model on the evolution of the magnetic field morphology to future work.

Another possibility to stabilise the HBI would be via strong magnetic fields, as the HBI growth rate is dumped on scales above \( H \gtrsim 20 \lambda \beta \) (Quataert 2008, Eq. 33), where \( \beta \) is the plasma-\( \beta \). In our clusters, the magnetic field strength after 3 Gyr of evolution ranges from \( 4 - 7.5 \) \( \mu G \) in the centre to \( 0.5 - 1 \) \( \mu G \) at \( r = 100 \) kpc. This means \( H \gtrsim 640 \) kpc in the centre and increases with radius, so the HBI is not suppressed by magnetic tension on scales relevant to the cluster cooling flow.

Finally, whistler-wave modulated conduction could significantly delay the HBI. As can be seen in Fig. 2, \(< b_r^2 >\) does indeed decrease more slowly for AGN_whistler than for AGN_cond, but there is still a significant reduction in comparison to the random initial conditions. The presence of Whistler waves therefore slows down, but does not eliminate, the evolution of the HBI in galaxy clusters. This is due to the fact that for realistic magnetic field strengths of a few micro Gauss in the cluster centre, the plasma-\( \beta \) in the cluster is sufficiently low such that \( f_{\text{sat,whistler}} \approx f_{\text{sat}} \) early on, as can be seen in Fig. 4. It is only as the magnetic field decays away slowly throughout the simulation due to the lack of volume-filling turbulence that plasma-\( \beta \) increases and \( f_{\text{sat,whistler}} \) drops at late times.

The conclusion that Whistler-limited saturation makes only a small difference to the evolution of the HBI is in agreement with work by Berlok et al. (2021), who studied the other conduction-driven instability, the magneto-thermal instability, which is active in cluster outskirts, and concluded that mirror instability-based suppression of thermal conduction has only a small impact. We note that using a reduced saturation-coefficient is a simplified approach. A more complete treatment would be to self-consistently modelling the whistler-wave energy density, source and loss terms (Drake et al. 2021), and that doing so is likely to significantly change the conclusions on the impact of whistler waves on conduction and the HBI in galaxy clusters.

\(< b_r^2 >\) increases again at small radii for both noAGN_cond and AGN_cond but for different reasons: in AGN_cond, the AGN randomises the magnetic field in the centre for an average \(< b_r^2 > \sim 1/3\). In noAGN_cond, a strong cooling flow develops, which causes radial inflows. Cooling flows are also responsible
for the high values of noAGN_nocond at all radii, and the late increase of $< b_z^2 >$ for AGN_nocond (See Section 3.2).

### 3.2. Thermal conduction and the cooling flow

The fact that both noAGN_nocond and noAGN_cond develop a strong cooling flow can be seen in Fig. 5. Both simulations without AGN build up unrealistically large quantities of cold gas in the cluster centre as the cooling of the hot ICM proceeds unimpeded. noAGN_cond cools more slowly than noAGN_nocond, but the reduction in total gas mass at 3 Gyr, $1.0 \times 10^{11} M_{\odot}$ for noAGN_cond versus $1.4 \times 10^{11} M_{\odot}$ for noAGN_nocond, is insignificant to the overall cooling flow.

To further understand the potential impact of thermal conduction, we add three simulations with a fixed $f_c$ : noAGN_iso and AGN_iso have $f_c = 1$, i.e. conduction is fully isotropic. AGN_third also has isotropic conduction but uses $f_c = 1/3$, equivalent to a fully tangled magnetic field. When $f_c$ is constant, any reorientation of the magnetic field will have no impact on the heat flux. It is only when conduction is isotropic (noAGN_iso), and therefore not influenced by the HBI, that conduction significantly reduces the cooling flow. This is in good agreement with work by Wagh et al. (2014), who also showed that isotropic thermal conduction significantly reduces the formation of cold gas in galaxy clusters. However, even isotropic thermal conduction is less efficient at regulating the cooling flow than AGN feedback, as can be seen by comparing noAGN_iso to any of the simulations with an AGN.

In the presence of AGN jets, cooling flows are strongly reduced as cold gas building-up in the cluster activates the AGN which prevents further cooling (see e.g. Li et al. 2015; Prasad et al. 2015; Li et al. 2017; Karen Yang & Reynolds 2016; Beckmann et al. 2019, for more details on AGN regulation of cluster cooling flows). Comparing AGN_nocond and AGN_cond in Fig. 5 shows that while the AGN effectively regulates cluster cooling and prevents a run-away cooling flow (top panel), anisotropic conduction makes little difference to the long-term evolution of the cluster.

To compare the impact of thermal conduction on the ability of the AGN to self-regulate the cluster, we define $\chi = \frac{\sum E_{\text{AGN,nocond}}}{\sum E_{\text{AGN,cond}}}$ (inset, Fig. 5), where $\sum E_{\text{AGN}(t)}$ is the cumulative energy injected by the AGN up to time $t$. In our simulations, $\chi \geq 1.2$, i.e. the simulation without conduction requires at least 20% more cumulative AGN energy than the case with conduction, for all simulations only while $t < 1$ Gyr, during which the cluster is still evolving away from the initial conditions. At late times, at an average value of $\chi = 1.24$ at $t > 2$ Gyr, $\chi$ remains elevated for AGN_third, but drops to $\sim 1$ for AGN_cond and AGN_whistler. This is in contrast to Kannan et al. (2016) and Barnes et al. (2019), who report $\chi = 1.2$–1.3 at all times. One possibility is that the HBI in Kannan et al. (2016) and Barnes et al. (2019) is being offset by turbulence injected by the large-scale cosmological environment. Support for this theory comes from the fact that fully tangled fields (AGN_third) in our simulations also show $\chi = 1.2$–1.3. However, Karen Yang & Reynolds (2016) used isolated clusters and also report $\chi \approx 1.5$. Another possibility is that as $\chi$ is very sensitive to the cluster mass (Karen Yang & Reynolds 2016) so the different $\chi$ could be due to different cluster masses or cluster profiles. A final possibility is that the higher resolution in our simulation ($\Delta x = 531$ pc Article number, page 5 of 7
have on average higher conduction (noAGN_nocond) but competes with the tangential-clusters (AGN_cr) increases the effective conductivity to values as low as $f_c = 0.1$ of Spitzer conductivity.

Such low levels of thermal conduction have no significant influence on the cluster cooling flow, or the AGN self-regulation thereof.

Whistler-wave driven saturation of thermal conduction reduces the magnitude of the HBI in galaxy clusters, but does not prevent it.

Even if the HBI was inefficient, and the magnetic field remained tangled, the resulting effective conductivity of $f_c = 1/3$ Spitzer is not sufficiently high to influence the AGN self-regulated cooling flow.

Only very high values of $f_c$, which would require predominantly radial magnetic fields, transport sufficient thermal energy to reduce the cluster cooling flow.

4. Conclusions

In this paper, we investigated whether the presence of a black hole spin-driven AGN jet can counteract the HBI in the centre of massive galaxy clusters and allow for efficient thermal conduction to aid in the long-term self-regulation of cluster cooling flows. We conclude that

- Spin-driven AGN feedback is able to randomise the magnetic field in the central 50 kpc of the cluster but not outside this region.
- Whether an AGN is included or not, the HBI remains very active in the region 50 - 300 kpc from the cluster centre, which reduces the effective conductivity to values as low as $f_c = 0.1$ of Spitzer conductivity.
- Only very high values of $f_c$, which would require predominantly radial magnetic fields, transport sufficient thermal energy to reduce the cluster cooling flow.

Our set of idealised simulations have demonstrated the inability of AGN jets alone to re-randomise the magnetic field after it has been tangentially aligned by the HBI, and, hence, to restore significant thermal conduction on cluster scales. We have shown that thermal conduction does affect the morphology of the magnetic field, which in turn could have important consequences for where cosmic ray energy is deposited in the cluster (see Beckmann et al. 2022). How the magnetic field evolves depends strongly on how conduction is modelled, and on the initial conditions of the magnetic field. We defer a more detailed study of the impact of magnetic field morphology on the evolution of galaxy clusters to future work, together with a study of the contribution of other sources of turbulence beyond AGN jets, such as large-scale inflows, stirring by satellites and other substructure (Ruszkowski & Oh 2011; Bourne & Sijacki 2017). Other phenomena to be considered are anisotropic thermal pressure due to Braginskii viscosity (Kunz et al. 2011).

References


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