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RESOLVING COLD FILAMENTS IN THE MULTIPHASE INTRACLUSTER MEDIUM WITH GPU–ACCELERATED SIMULATIONS

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Abstract. Numerous observational surveys have pinpointed the presence of multiphase structures in the inner tens of kpc of most cool–core clusters. While the exact origin of these filamentary structures of cold gas is still highly debated, active galactic nuclei are thought to play a key role in their formation and evolution, by injecting turbulence in thermally unstable regions of the intracluster medium.

We present a set of GPU–accelerated MHD simulations of an idealized cool–core cluster. We probe the structure of the filaments down to a resolution of 25 pc. We conclude that magnetic fields are crucial to produce realistic filamentary structures, and that the filaments are clumpy as they contain a complex hierarchy of cold clouds whose sizes span from kpc down to our resolution limit.

Keywords: galaxies: clusters: intracluster medium - galaxies: jets - galaxies: clusters: general - methods: numerical - magnetohydrodynamics

1 Introduction

Galaxy clusters are massive structures and young structures containing up to thousands of galaxies. While galaxies themselves only contribute marginally to the overall galaxy cluster's mass, dark matter and the intracluster medium (ICM), a hot plasma filling the volume between galaxies are responsible of ∼95 % of the overall cluster's mass budget (Andreon 2010; Laganá et al. 2013). The ICM constantly undergoes cooling processes, such as Bremsstrahlung, which makes it visible in the X–ray domain (Boehringer & Hensler 1989). In some of these clusters, designated as "cool–core" clusters, a central overdensity of gas is visible. The typical cooling time of these overdensities can reach down to only a few tens of Myr, suggesting the presence of a massive flow a cooling gas with mass flux up to $10^3\,\mathrm{M}_\odot/\mathrm{yr}$ (Fabian 1994; Peres et al. 1998). In the absence of any observational signature of such cooling flows (Peterson et al. 2001), several processes possibly preventing the overcooling of the ICM have been proposed and tested, such as conduction (Zakamska & Narayan 2003), shock heating (Ruszkowski et al. 2004), or cosmic rays heating (Guo & Oh 2008). The key role of the active galactic nuclei (AGN) is now accepted as an effective heating source, able to offset cooling, possibly sustaining a self-regulation of the clusters over billions of years.

Cool-core clusters are nevertheless not devoid of cold gas, as recent observations have highlighted the ubiquity of multiphase structures at the center of nearly all observed cool-core clusters (Olivares et al. 2019). A mezmerizing example is NGC 1275, the brightest cluster galaxy (BCG) of the Perseus cluster. X–ray, optical and radio surveys performed in the last three decades have unveiled a nebula of ionized and neutral gas extending up to ∼ 50 kpc away from the galaxy's center (Cowie et al. 1980; Fabian et al. 2000; Conselice et al. 2001; Wilman et al. 2005; Salomé et al. 2006). The exact origin of this cold gas remains unclear. Although it is accepted that thermal instability and turbulence injected by the AGN outflows hold a key role, state-of-the-art simulations struggle to reproduce realistic morphologies of the cold phase, either due to missing physics (such as magnetic fields or possibly cosmic rays), or numerical limitations.

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2 Numerical methods

In Fournier et al. (2024), we use the `AthenaPK` code (Grete et al. 2022), a portable version of `Athena++` (Stone et al. 2020) to simulate an idealized cool–core cluster for a duration of 1.8 Gyr, down to spatial resolutions of 25 pc. We include radiative cooling, magnetic fields and a model for AGN feedback. Accreted cold material is redistributed into kinetic, thermal and magnetic energy. We assume a radiatively thin intracluster medium of half-solar metallicity. We run a fiducial simulation with magnetic field, as well as a purely hydrodynamical one for comparison.

3 Results

3.1 Morphology

We find that although cold structures are ubiquitous in both our fiducial and purely hydrodynamical runs, the effect of magnetic fields has a major impact on their morphology. In purely hydrodynamical runs, the clump distribution is unstructured and lacks the typical filament morphology seen in observational surveys. In the absence of magnetic fields, the cold gas is also found to quickly (ie. a few hundreds of Myr after the AGN turns on) settle into a massive disk with a radius of $\sim$ 5 kpc, as reported in previous work using hydrodynamical setup (Li & Bryan 2014a,b; Beckmann et al. 2019; Qiu et al. 2019). When magnetic fields are included, the morphology of the cold gas follow a complex distribution of clumps, gathering together to form massive filaments of $\sim 10^9\,\mathrm{M}_\odot/\mathrm{yr}$. In Fig. 1, we present mock Hα observations of our simulated BCG at $t = 1025$ Myr. The left panel shows an unsmoothed image, while the middle one is convoluted with a Gaussian filter to match the spatial resolution of the Muse instrument. A Muse observation of the Centaurus cluster is shown in the right panel for comparison (Olivares et al. 2019). The left and middle plot suggest that many substructures of the filaments might be unresolved and washed away by the combined effects of limited angular resolution and atmospheric seeing of ground based telescopes.

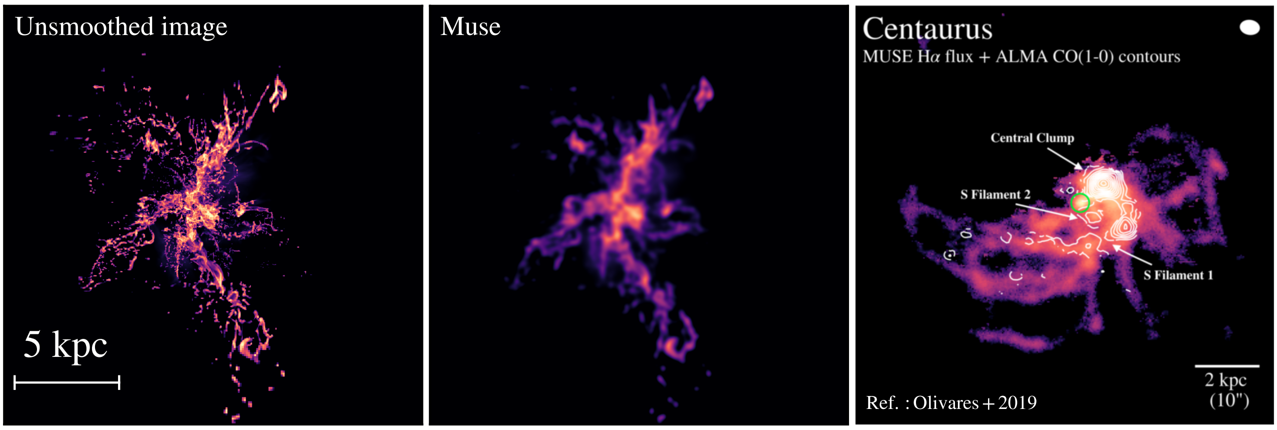

Fig. 1. Left and middle panel: mock Hα images showing the cold structures in our fiducial MHD run at $t = 1025$ Myr. The middle image is the same image as the left one, convoluted with a Gaussian filter to match the spatial resolution of the Muse instrument, assuming that our simulated cluster is at the same distance as the Perseus cluster. **Right**: Fig. 2 from Olivares et al. (2019) for comparison.

To study the properties of the filaments structure, we use a clump finding algorithm to evaluate the statistical distribution of mass, radial velocity and magnetic field strength across filaments. We apply this clump finding algorithm to five different filaments we identified within our fiducial run. The main results are presented in Fig. 2. The left panel shows the cumulative mass fraction of clumps with increasing mass, which suggests that a large fraction of the overall filament's mass is carried by the most massive clumps. As visible in the middle panel, we find that the mass distribution of the clumps present in each filament follow a power-law of slope $\alpha \sim -0.7$. The velocity distribution of the clumps is rich as it spreads from $\sim -400\,\mathrm{km\,s^{-1}}$ to $\sim +400\,\mathrm{km\,s^{-1}}$, although being skewed towards negative value, suggesting that filaments are mostly infalling structures. We also find the filaments to be largely supported by magnetic pressure. Typical field strength in the cold phase is around $100\,\mu$G, and up to $200\,\mu$G locally.

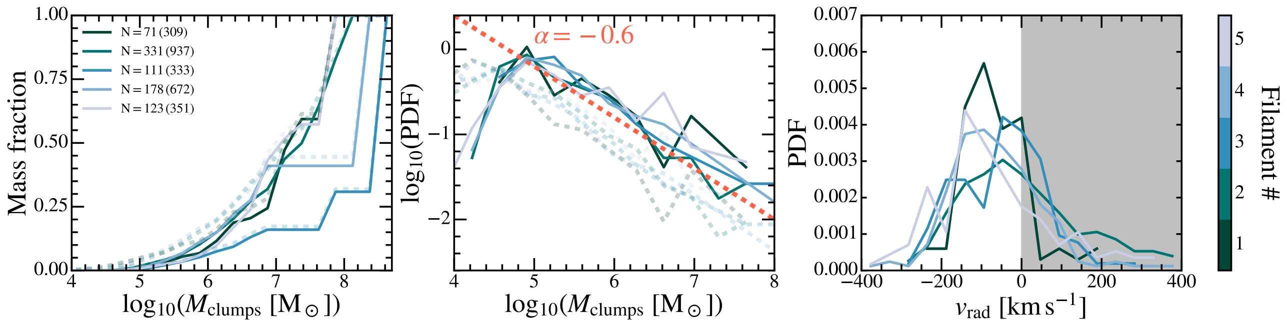

Fig. 2. Normalized distribution of clumps for each of the five studied filaments. The solid line corresponds to the sample of clumps obtained while excluding clumps of less than ten cells, while the dashed line is the full sample of clumps with no restriction. **Left panel**: cumulative fraction of mass carried by clumps of increasing mass. **Middle panel**: mass distribution of clumps. **Right panel**: radial velocity distribution of clumps.

3.2 Formation

In Fig. 3, we present phase diagrams showing the average volume–weighted radial velocity of the cold gas for five filaments found in our simulation. For four of the five filaments, the radial velocity of the cold phase is initially positive as a few hundreds of clumps moves upwards while coupling with the AGN jets. After a few tens of Myr, these clumps stall and fall back towards the center of the cluster due to gravity. More gas condense and the filament mass increases until is reach $\sim 10^{8-9}\,M_{\odot}/yr$. In one case (namely filament #3), the gas filament structure seems to emerge solely out of cooling ICM, as its bulk motion is preferably infalling throughout its whole lifetime. The formation of this specific filament is spatially and temporally correlated with the inflation of an AGN bubble, suggesting that the turbulence injected at the edge of this bubble is triggering cooling.

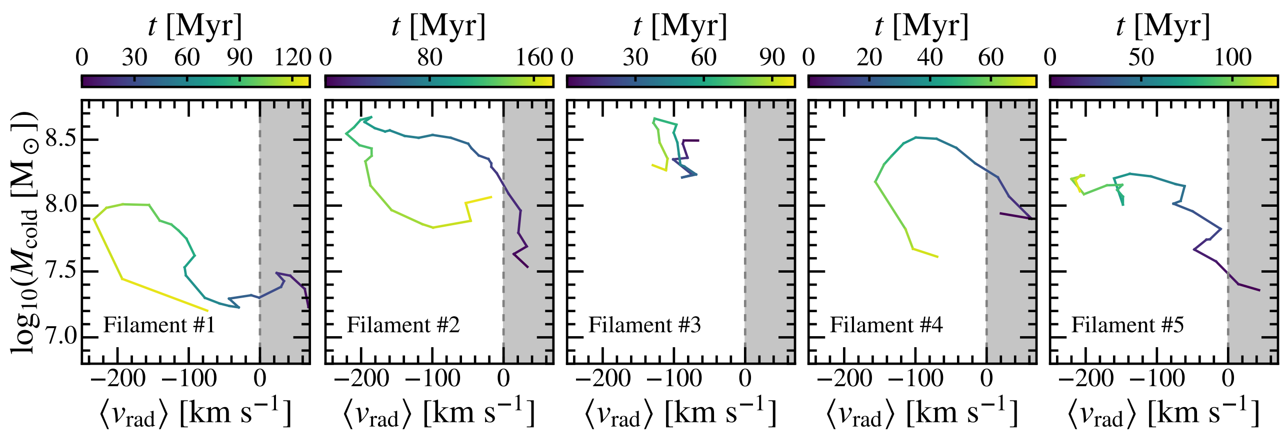

Fig. 3. Time evolution of the volume–weighted radial velocity of the cold gas for five filament found in our fiducial simulation, as a function of their total mass.

4 Conclusion

The main conclusions of our work are as follows:

- The magnetic fields play a key role at shaping the structures of cold gas in cool–core clusters. These suppress the formation of massive cold disks, ubiquitous in purely hydrodynamical setup, and are responsible of the filamentary shape of the cold gas distribution.
- The filaments are clumpy and many of their internal substructures are likely to be unresolved by current optical surveys.

- Magnetic pressure largely dominate the pressure support of the filament, as it is on average one order of magnitude above the thermal pressure within the cold phase.
- While the bulk motion of the filament is found to be preferentially infalling, for four of the five investigated filaments the formation sequence starts by the uplifting of cold clumps, which might act as seed for condensation.

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