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Ubiquitous cold and massive filaments in brightest cluster galaxies

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Abstract. The origin of the mysterious multiphase filamentary structures surrounding Brightest Cluster Galaxies (BCGs) remains unknown. We present Atacama Large Millimeter/submillimeter Array (ALMA) and Multi Unit Spectroscopic Explorer (MUSE) observations for a sample of 15 BCGs to investigate the origin and life-cycle of the gas. Those observations show clumpy and massive molecular filaments, preferentially located around the radio bubbles inflated by the active galactic nuclei (AGN). We investigate where the cold gas condenses from the intra-cluster medium, by comparing the radial extent of the filaments with predictions from numerical simulations.

Keywords. galaxies: active, galaxies: jets, galaxies: clusters: intracluster medium

1. Motivation

The classical cooling-flow model fails in the absence of an external non-gravitational heating mechanism needed to compensate for catastrophic radiative cooling in the intra-cluster medium (ICM) of galaxy clusters. Feedback from an AGN contributes to offset the cooling through bubbles inflated by radio jets launched from massive black holes. However, it cannot completely offset the cooling as the BCGs harbors a complex multiphase medium of extended warm and cold reservoirs of gas, whose physical origin remains unknown. Recent theoretical analyses and simulations have suggested that the hot atmospheres can become thermally unstable locally when the ratio of the cooling to free-fall timescales, t_{cool}/t_{ff} falls below $\sim$10−20 (e.g., Voit *et al.* 2017), or when the ratio of the cooling time over the eddy turn-over timescale, t_{cool}/t_{eddy}, is close to unity (Gaspari *et al.* 2018). The cold gas has likely cooled in-situ from (i) either low-entropy gas that has been uplifted by the bubbles at an altitude where it becomes thermally unstable (ii) or by direct thermal instability of small perturbation in the hot halo (see the introduction of Tremblay *et al.* (2018) for a detailed description of the different scenarios). To investigate the nature and life-cycle of those enigmatic filaments we used ALMA observations that map the kinematics and morphology of the cold molecular gas phase of 15 BCGs (3 from new ALMA observations and 11 gathered from the ALMA archive). We compare ALMA observations with new MUSE data that map the kinematics and morphology of the warm ionised gas.

2. Results and Discussion

Molecular filaments: From the sample studied with ALMA, we found that most of the sources show extended unrelaxed structures with disturbed motions along the filaments. In those systems, the molecular distribution usually consists of a nuclear emission component closely related to the BCG's core and a set of extended massive clumpy filaments, with cold molecular masses of a few $\sim 10^{8}-10^{10}$ $M_{\odot}$, which are preferentially

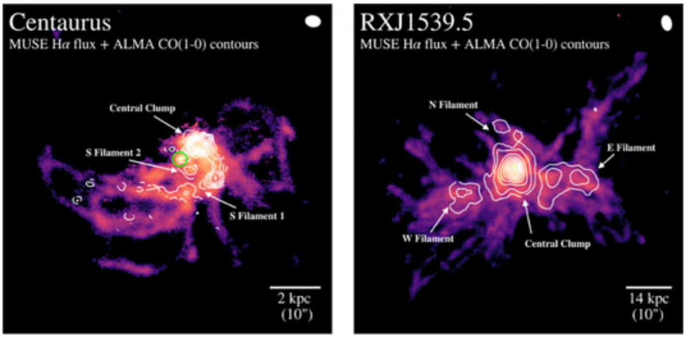

Figure 1. Hα flux maps from MUSE observations overlaid with contours from the CO(1-0) integrated intensity maps for two of the new ALMA sources: Centaurus (left panel) and RXCJ1539.5-8335 (right panel). The co-spatial and morphological correlation between the warm ionised and cold molecular nebulae is clear in these maps. From Olivares *et al.* (2019)

located around the radio bubbles inflated by the AGN or beneath the X-ray cavities. While two systems, Abell 262 and Hydra-A, are well described by relaxed structures showing ordered motions within a compact ($\sim$2$-$5 kpc length) thin ($\sim$kpc) rotating disc located at the very centre of the BCG. This cold gas disc may be an essential step in driving the gas into the vicinity of the AGN. In an AGN-regulated scenario, one indeed expects that a fraction of the cooled gas will eventually fuel the SMBH to maintain the powerful jets which are injecting mechanical energy into the ICM. The cold molecular gas in some of the galaxy cluster cores shows disturbed velocities, while others show smooth velocity gradients in substructures indicating either inflow or outflow of gas. The velocities of the cold clouds are slow through the molecular gas, lying in a range of 100$-$400 km s^{-1}. Those molecular velocities are inconsistent with the scenario of simple freely in-falling gas, where higher velocities are expected. These small velocity being below the escape velocity of the galaxy, the outflowing cold clouds should eventually fall back and fuel the central AGN. The superposition of inflowing and outflowing filaments along the line of sight can mix and cancel velocities structures.

Evidence supporting that cold and ionised emission arises from the same ensemble of clouds: The molecular gas is generally spatially distributed along the brightest emission from the warm ionised nebula (see Fig. 1). It also appears that the cold molecular and warm ionised gas share the same overall velocity structure. The comparison between Hα and CO(1-0) emissions indicates that the Hα velocity dispersion is broader than the CO one by a factor of $\sim$2. This can occur because the lines-of-sight are likely to intersect more warm gas than cold clouds, and also that the warm gas is more likely to be turbulent with higher velocities. The Hα-to-CO flux ratios are close to unity all along the nebula with a lack of significant radial gradients, which indicate a local excitation mechanism. It is also possible that the molecular filaments are as long as those seen in Hα. We derived expected total molecular masses, based on the Hα-to-CO flux ratios, which are higher than those one observed from ALMA by a factor of 1.2 or up to 6. Future high sensitivity ALMA observations are needed to confirm this. Such correlations can also be interpreted as the manifestation of a common origin, as the condensation of low-entropy gas via the top-down multiphase condensation cascade through thermal instabilities.

Origin of the cold gas: Using the ACCEPT (Archive of Chandra Cluster Entropy Profile Tables) sample X-ray ICM properties (Cavagnolo *et al.* 2008), we found that filaments always lie within the low-entropy and short cooling-time gas. As described in the

Chaotic Cold Accretion (Gaspari & Churazov 2013) or precipitation models (Voit *et al.* 2017), an important radius is when the cooling time exceeds the free-fall time by no more than a factor of 10, or when the t_{cool} is below 1 Gyr. We find that the extent of the filaments roughly corresponds to the radius where t_{cool}/t_{ff} is close to its minimum, which is always between 10 and 20. We also compared the ratio, t_{cool}/t_{eddy} as a function of the extent of the filaments, where the eddy turnover time is related to the turbulence injection scale. We find that the filaments lie in regions where this ratio is less than $\sim$1. So the AGN bubbles may be powering the turbulent energy, which triggers gas cooling by compression and thermal instabilities. In addition, we showed that the energy contained in the AGN-cavities is enough to drag up some low-entropy gas in a region distant from the center. So the radio-AGN can prevent an overcooling on large scales, and it is also the engine that may trigger the cold accretion along filamentary structures and provide the material to feed the regulated feedback cycle. The full condensation process includes bubbles inflation, uplift and cocoon shocks. As a result, one or several mechanisms may dominate, i.e., precipitation, stimulated feedback, or even sloshing. In our sample, all of these processes seem to be responsible (to some degree) for the condensation of the cold gas. Further deep observations and velocity structure information of the hot phase will be crucial to clear up the dominant process.

References

Cavagnolo, K. W., Donahue, M., Voit, G. M., *et al.* 2008, *ApJ*, 683, L107
Gaspari, M. & Churazov, E. 2013, *A&A*, 559, A78
Gaspari, M., McDonald, M., Hamer, S. L., *et al.* 2018, *ApJ*, 854, 167
Olivares, V., Salome, P., Combes, F., *et al.* 2019, *A&A*, 631, A22
Tremblay, G. R., Combes, F., Oonk, J. B. R., *et al.* 2018, *Apj*, 865, 13
Voit, G. M., Meece, G., Li, Y., *et al.* 2017, *ApJ*, 845, 80

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