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Cold Gas in Outflow: Evidence for Delayed Positive AGN Feedback

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Abstract. Multiphase outflows driven by active galactic nuclei (AGN) have a profound impact on the evolution of their host galaxies. The effects of AGN feedback are especially prominent in the brightest cluster galaxies (BCGs) of cool-core clusters, where there is a concentration of gas in all phases, ranging from cold molecular gas to hot, $> 10^7$ K ionized plasma. In this proceeding I describe recent simulation efforts to understand the formation and evolution of the 10-kpc-scale Hα-emitting filaments driven by AGN activities. Combined with observed star formation regions co-spatial with the filaments, this feedback mechanism can directly contribute to the growth of the central galaxy, albeit delayed by the characteristic radiative cooling timescale, ~ 10 Myr, of the outflowing plasma.

Keywords. ISM: jets and outflows, galaxies: active, cooling flows, methods: numerical

1. Introduction

The rich concentration of gas in the brightest cluster galaxies (BCGs) of cool-core clusters provides some of the best environments for observing and understanding the impact of AGN feedback. Due to the radiative cooling of the hot intracluster medium (ICM), a cooling flow of $\sim 10 - 100\, M_\odot\ \mathrm{yr}^{-1}$ is expected to continuously feed the growth of the BCG (Fabian 1994). In reality, the star formation rates of these galaxies are around 10% or less of those inferred from cooling (McDonald et al. 2018). X-ray cavities filled with radio emission indicate that AGN jets can inflate bubbles and do mechanical work to heat the intracluster medium (Bîrzan et al. 2004; McNamara and Nulsen 2007). On the other hand, cold gas often resides in elongated filaments radially connected to the central supermassive black hole (SMBH; Conselice et al. 2001; McDonald et al. 2012; Gendron-Marsolais et al. 2018, see also Fig. 1), suggesting that the AGN is also responsible for the formation and distribution of the Hα-emitting filaments.

In particular, in the nearby Perseus cluster, two irregular filament structures, a.k.a the horseshoe filament and the blue loop, are located about 20 kpc on opposite sides of the central SMBH, indicating that they were driven by the same episode of AGN activity, such as jets or winds. Unlike other radial filaments, however, these two structures have azimuthal components that are not readily explained by outflows driven from the central AGN. Meanwhile, some cold gas in these filaments has recently collapsed and formed stars, with typical ages less than 10 Myr (Canning et al. 2014). If the filaments indeed were driven by AGN activities, their formation constitutes a mechanism for AGNs to delay and offset the central star formation fueled by the cooling flow.

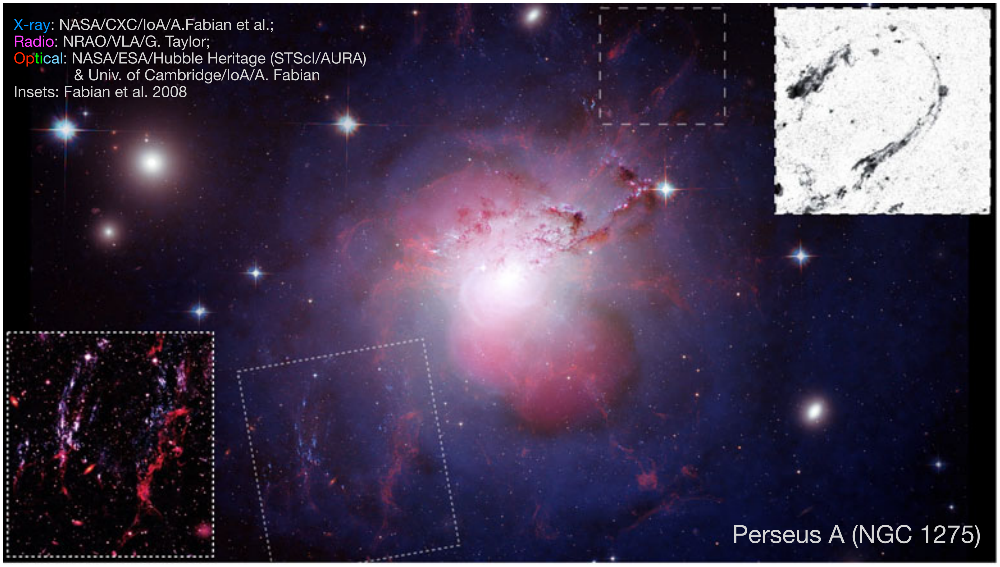

Figure 1. A composite image showing the various observational signatures of AGN feedback in the center of the cool-core Perseus cluster. Two loop-like cold filament structures are located on opposite sides of the central AGN (insets; Fabian et al. 2008), indicating that they were driven by the same bipolar AGN outburst. The star formation regions co-spatial with the Hα filaments (e.g., the "blue loop" in the bottom left inset) also indicate that AGN feedback may contribute positively to the galaxy growth, offset from the nucleus.

2. Simulations of AGN Feedback in Galaxy Clusters

In order to study the impact of AGN feedback on the evolution of galaxy clusters, as well as to understand the origin of the cold filaments, in both radial and azimuthal formations, we performed a series of simulations using Enzo (Bryan et al. 2014) + Moray (Wise and Abel 2011). In the large-scale ($\sim$ Mpc), long-duration (~ 10 Gyr) radiation-hydrodynamical simulations, we found that the AGN drives multiphase outflows that are responsible for both the X-ray cavities and the extended cold filaments in BCGs (Qiu et al. 2019b). Positive correlations can be drawn between AGN luminosity and properties of the filaments, such as filament mass, spatial extent, as well as Hα luminosity (Qiu et al. 2019a). The velocity dispersion of the filaments, however, depends primarily on the turbulent interactions between the ICM and the outflows, and are therefore not strongly correlated with the AGN luminosity (e.g., the standard deviation of cold gas velocity in Fig. 3, $\sim 100 - 200\,\mathrm{km\,s^{-1}}$, similar to the observed filament velocity dispersion values in the Perseus cluster; Gendron-Marsolais et al. 2018).

The similarities between the simulated filamentary nebula and those in observations of the Perseus cluster motivated us to examine more closely the formation mechanism of the cold gas in a follow-up study (Qiu et al. 2020). A strong constraint from observations of the filaments is that the line-of-sight velocities are mostly below a few hundred $\mathrm{km\,s^{-1}}$. Apart from the projection effect, if the cold gas were directly ejected from the nucleus, it requires both $> 1000\,\mathrm{km\,s^{-1}}$ speeds and unrealistically strong shielding from the shock heating and the hot ambient ICM to reach beyond 10 kpc. Our analysis however indicates that the filaments form out of ionized AGN-driven outflows launched from the central 1 kpc†, with temperature $\lesssim 10^7$ K and characteristic cooling time below 10 Myr. Although

† The origin of the filament gas is confirmed using a tracer fluid injected in the central 1 kpc of the simulated cluster. From this region, the outflowing gas may include a mixture of injected AGN wind plasma, shocked and entrained circumnuclear gas, as well as the ICM. Higher-resolution simulations focused on this central region are required to further dissect and understand these components.

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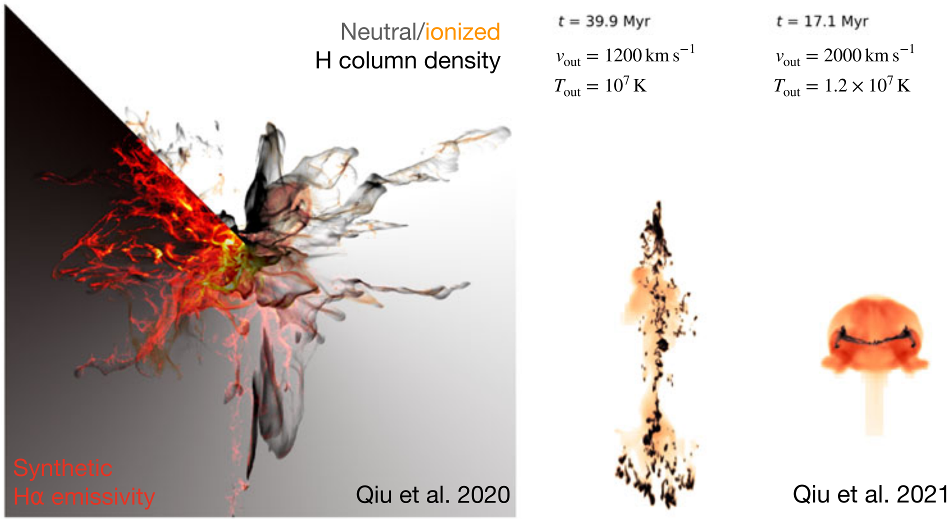

Figure 2. Left: A composite image showing the ionized and neutral hydrogen column densities, as well as the synthetic Hα emissivity, in the simulated galaxy cluster undergoing an AGN outburst (Qiu et al. 2020). Filaments of Hα-emitting gas extends ~ 30 kpc from the central AGN. Right: Snapshots from a high-resolution follow up simulation study focusing on the individual filament morphology as a function of initial outflow properties (velocity $v_{\rm out}$ and temperature $T_{\rm out}$; Qiu et al. 2021a). Both longitudinal and transverse filaments may form with respect to the outflow direction (up).

the initial speeds are high, the ram pressure deceleration from the ICM significantly reduces the outflow velocity before cold gas forms about 10 kpc away from the nucleus (Figs. 2, 3).

While the simulated filaments are visually similar to the observed filaments, the resolution required to study the filaments is much higher than those employed in cluster-scale simulations (~ 0.1 kpc, which is similar to or larger than the width of individual filaments). In order to characterize the filament evolution, as well as to resolve the interactions between the filament and the ambient plasma, we use high-resolution simulations (with the smallest resolution size of ~ 30 pc) to further study the dynamical and morphological evolution of the cold gas in radiatively cooling AGN-driven outflows embed in the ICM (Qiu et al. 2021a). Using the parameter space found in Qiu et al. (2020) and the line-of-sight velocity constraints from observations, we vary the initial velocity and temperature of the outflowing plasma to examine the structure of the emergent cold gas. The evolution of the center of mass can be reasonably well described by a 1D model comprising radiative cooling and ICM ram pressure (Fig. 3). In addition to longitudinal filaments parallel to the outflow direction, this study uncovered a mechanism for transverse filaments perpendicular to the direction of motion to form – when the outflowing plasma is marginally thermally stable between radiative cooling and heating through mixing with the ambient ICM (Fig. 2). The ring of cold gas in the right panel of Fig. 2 can potentially explain the origin of the loop-like filaments and star formation region in the Perseus cluster.

Besides the positive AGN feedback mechanism revealed by the irregularly shaped filaments, the location and mass of the filaments can be used to constrain the energetics of past AGN outbursts. Observationally, large amounts of molecular gas have been discovered co-spatial with the Hα filaments. Using cold gas mass measurements ($\sim 10^8\ M_\odot$;

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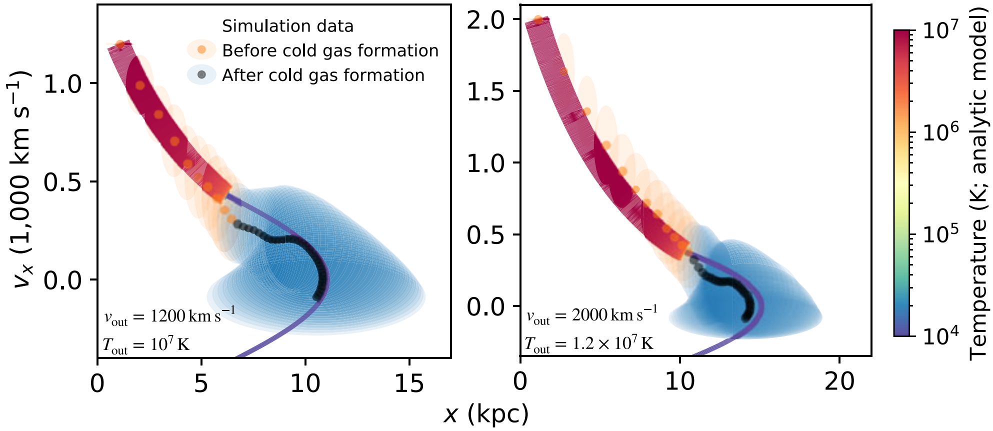

Figure 3. Evolution of the center of mass velocity as a function of distance traveled for the simulated outflows in Qiu et al. (2021a), compared with the 1D model in Qiu et al. (2020). The size of the ellipses centered on the data points represents the standard deviation ($\pm\sigma$) of the simulated cold gas properties. The initial velocity and temperature of the outflows ($v_{\rm out}$, $T_{\rm out}$) are shown in each panel, corresponding to the two cases in Fig. 2. Cold gas forms $\sim 10\,$Myr after the outflows are launched, consistent with the radiative cooling timescale of the $\sim 10^7$ K plasma.

Salomé et al. 2008, 2011) and the initial outflow velocity inferred from the simulations, the AGN kinetic output can be estimated as

$$E_{\rm kin} \approx 10^{57} \frac{M_{\rm out}}{10^8\,M_\odot} \left(\frac{v_{\rm out}}{1000\,{\rm km\,s^{-1}}}\right)^2 \,{\rm erg}. \tag{2.1}$$

Combined with the cooling timescale of the original outflow ($\sim 10\,$Myr), and the dynamical timescale for different generations of filaments to evolve to their observed morphological states ($\sim 10 - 100\,$Myr), these simulations can also help to reconstruct the history and constrain the duty cycle of the AGN activity in the past few hundred million years.

3. Summary

Using a series of simulations centered on the BCGs of cool-core clusters, we study the interplay between AGN feedback and the multiphase gas in the ICM. Besides the hot outflows which maintain the thermal balance of the plasma and prevent it from collapsing and fueling a central starburst (see Qiu et al. 2021b, for a study on the heating of the ICM delivered by hot outflows), in this proceeding I focus mainly on the formation and evolution of the cold gas driven by AGN activities. Our simulations indicate that the component of the outflow with characteristic cooling timescale below 10 Myr is responsible for the formation of the extended filamentary nebulae. Depending sensitively on the initial properties, both longitudinal and transverse filaments may form in the outflows. Evidently in the nearby Perseus cluster, some of the cold gas in these filaments has collapsed and formed stars in the recent few Myr. The feedback mechanisms uncovered in these works therefore demonstrate that AGN activities in gas rich environments, such as in the BCGs of galaxy clusters, can tightly control both the thermal balance of the hot gas reservoir and the scattered star formation in and around the host galaxies.

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