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An idealized setup for cosmological evolution of baryonic gas in isolated halos

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Abstract. We use hydrodynamical simulations to study the evolution of baryonic gas in a cosmologically evolving dark matter halo. We model both the inner and outer regions of the halo using a density profile that transitions from an inner NFW profile to a flat profile far from the halo. Metallicity-dependent radiative cooling and AGN jet feedback are implemented, which lead to heating and cooling cycles in the core. We analyze the evolution of gas and the central supermassive black hole (SMBH) across cosmological time. We find that the properties of the gas and the SMBH are correlated across halo masses and feedback efficiencies.

Keywords. Galaxy: active-Galaxies: intergalactic medium-Galaxies: halos

1. Introduction

According to the standard ΛCDM (Λ cold dark matter) paradigm of structure formation in the Universe, the evolution of galaxy clusters is primarily governed by dark matter halo dynamics. Whereas, in addition to following the dark matter gravity, the gas (which constitutes $\sim 80\%$ of baryons within massive halos) is strongly affected by radiative cooling and feedback heating powered by accretion onto a central supermassive black hole (SMBH). Modern cosmological galaxy formation simulations evolve baryons including these processes, and with sub-grid models for star formation and SMBH growth.

Another class of numerical simulations consists of idealized halo simulations that focus on various aspects of baryonic physics. While these simulations provide insight into gas evolution, they typically lack cosmological evolution. Most of the idealized simulations of isolated halos assume a static dark matter halo (e.g. Prasad et al (2015)), and various important parameters (such as the metallicity of the IGM, e.g. Choudhury et al (2019)) are not evolved cosmologically. While modern galaxy formation simulations reach very high resolutions, they cannot achieve the resolution achievable in single-halo simulations (e.g., zoom-in simulations). Therefore, to focus on the most basic physical processes governing the halo gas, we carry out simulations of the halo gas in cosmologically growing halos. This approach can provide a useful middle ground between fully cosmological and isolated, cosmologically non-evolving halo simulations.

2. Setup

We solve the standard hydrodynamical equations in spherical coordinates in 2D with external gravity due to the dark matter halo, radiative cooling, and mass and momentum injection due to AGN jet feedback, using the astrophysical MDH code PLUTO (Mignone et al (2007)). The dark matter halo density profile is modelled according to Diemer & Kravtsov (2014), who proposed a new density profile that accurately models

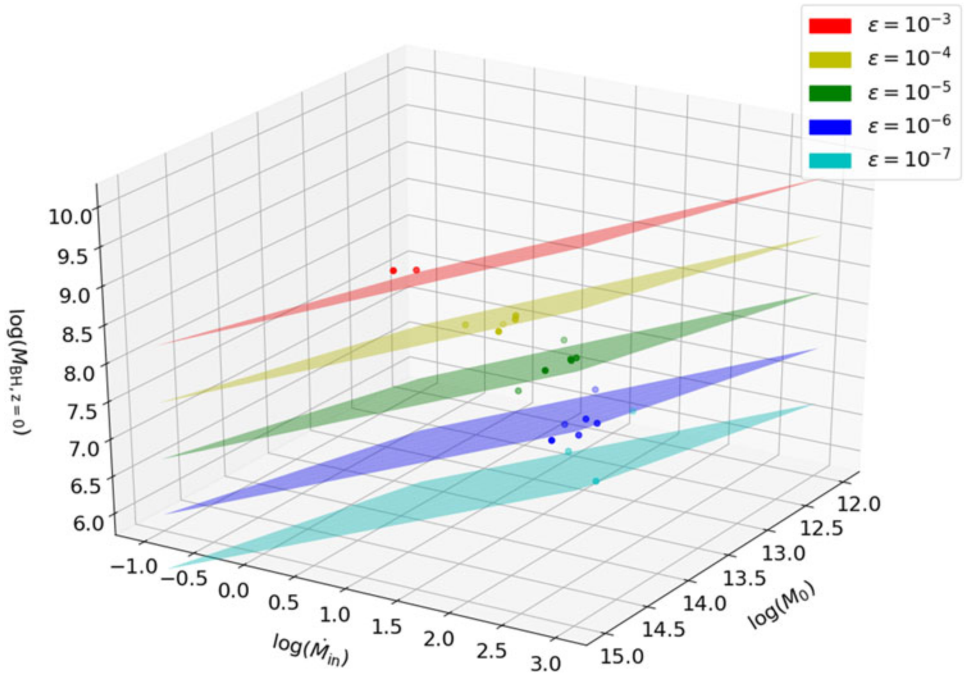

Figure 1. Properties of the halo gas and central SMBH in the $\log(M_0)$ - $\log(\dot{M}_{\rm in})$ - $\log(M_{\rm BH,z=0})$ space for different feedback efficiencies.

the dark matter density beyond the virial radius. Metallicity-dependent radiative cooling and AGN jet feedback are implemented, which strongly affects the dynamics of the gas in the halo core. The feedback is modelled by the accretion of cold gas onto a central SMBH, and is characterized by the feedback efficiency ϵ. Our simulations start at $z=6$, with an initial gas density profile that follows the dark matter as $\rho_{\rm g} = 0.2\rho_{\rm DM}$.

3. Results and Discussion

Radiative cooling and AGN feedback lead to a self-regulating cycle of heating and cooling in the halo core is formed. Cooling initially dominates and cold gas flows toward the center, leading to a large accretion rate onto the SMBH. This launches powerful jets that heat up the gas, forming low density bubbles and cavities. The hot gas mixes with the surrounding medium, which eventually leads to decrease in the accretion rate and jet power. Cooling starts to dominate again, and the cycle is repeated.During the heating portion of the cycle, the jet power, accretion rate onto the black hole, and the value of $\min(\rm t_{cool}/t_{ff})$ increase, while the cold gas mass within 5 kpc decreases. The opposite is true for the cooling portion of the cycle.

The effect of the AGN feedback on the halo gas can be quantified by the suppression of the cold gas inflow rate relative to the respective cooling flow. Runs with greater feedback efficiency lead to greater suppression because the gas is heated and ejected from the core to a greater degree. This also leads to longer feedback cycles, as the gas takes longer to cool again. Massive halos have deeper potential wells, so a greater amount of energy is required to disrupt the core to the same degree.

The accretion rate onto the central SMBH is initially limited by the Eddington rate, leading to exponential growth of the black hole. This is the quasar phase of black hole evolution. The duration of the quasar phase is longer for lower black hole seed masses.

After the quasar phase, the accretion rate is no longer limited by the Eddington rate. This slower, self-regulated growth is the radio phase.

We find that the present-day black hole mass, the halo mass, the cold gas inflow rate, and the feedback efficiency are strongly correlated, and the values lie on a fundamental plane, as shown in Figure 1.

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