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Direct collapse to SMBH seeds in cosmological halos with radiation transfer

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Abstract. We present results of our zoom-in cosmological hydrodynamic simulations of direct collapse (DC) to supermassive black hole (SMBH) seeds with radiative transfer (RT). The DC has been modeled in dark matter halos of $\sim 10^8\,\mathrm{M}_\odot$, using adaptive mesh refinement (AMR) code Enzo. For the first time, the baryonic collapse has been followed down to 10^{-7} pc ($\sim$0.01 AU) with on-the-fly RT and the flux-limited diffusion (FLD) approximation. We find a complex behavior involving accretion flow and associated outflows driven by the radiation force. The resulting gas dynamics around the central density peak differs profoundly from that in previous works which adopted adiabatic approximation in the core. The core forms with a photosphere at $\sim$1 AU, and its growth starts to saturate at $\sim 100\,\mathrm{M}_\odot$. The unrelaxed core radiates intermittently near the Eddington luminosity, correlated with strong anisotropic outflows.

Keywords. hydrodynamics, black hole physics, radiative transfer, accretion, methods: numerical

1. Introduction

The DC appears as a leading scenario for the formation of SMBH seeds at high redshift. SMBHs with masses of $M_{\mathrm{BH}} \sim 10^9\,\mathrm{M}_\odot$ have been discovered at $z > 6$. However, to grow such objects from Pop III star remnants ($\sim 10-100\,\mathrm{M}_\odot$) within several 100 Myr from $z \sim 20$ to 7, it requires either continuous Eddington accretion or episodic super-Eddington accretion. DC allows formation of more massive seeds with $10^4-10^6\,\mathrm{M}_\odot$ at $z \sim 10-20$, giving a head start for SMBH formation. So far, attempts to simulate DC have assumed an adiabatic equation-of-state in the optically-thick regime, when radiation is generated within the flow. In this case, the collapse is terminated and a supermassive star formation is subsequently assumed, however, its formation has never been demonstrated self-consistently in ab initio radiation hydrodynamic simulations.

2. Method and Results

We use Enzo-2.4 AMR code with an RT module (Reynolds *et al.* 2009) heavily modified by our group. For initial conditions, we use MUSIC code (Hahn & Abel 2011) on a comoving box of $1\,h^{-1}$Mpc with 128^3 DM particles. In this pathfinder run, we identify a

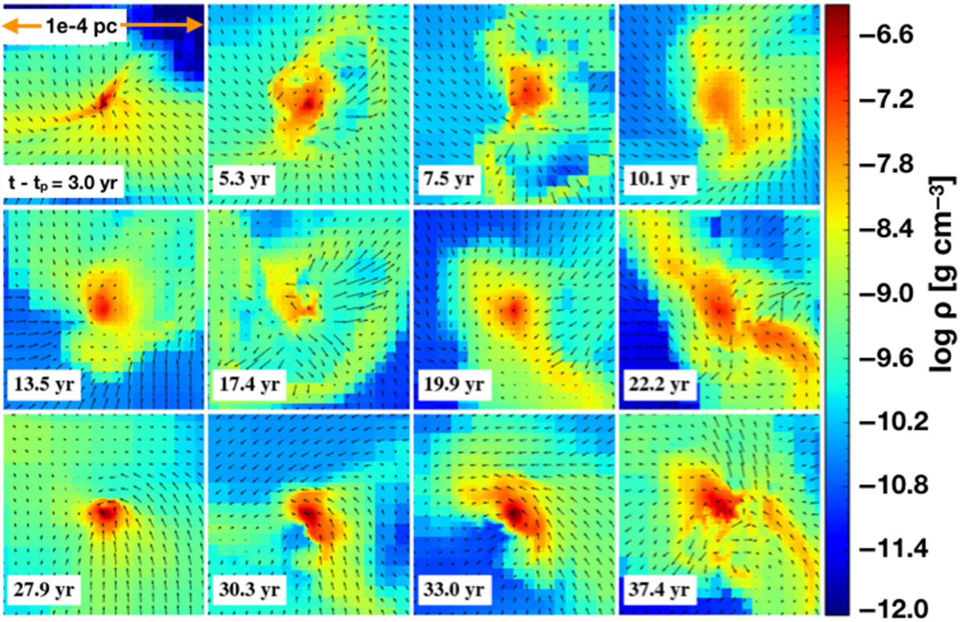

Figure 1. The FLD collapse. Evolution of the innermost density slice (color map) with superposed velocity vectors. The size of each panel is 10^{-4} pc, and the indicated time is measured from the moment when the photosphere formed. Recurrent anisotropic outflows are driven by radiation and thermal pressure gradients and form expanding shells, mixing with the accreting flow.

zoom region of $0.18\,h^{-1}$Mpc with 512^3 initial grid, and use AMR to simulate the collapse down to 10^{-7} pc with maximum refinement of 32–36 levels. The primordial opacity has been adopted from Mayer & Duschl (2005). Cooling by metals and dust are ignored for $z > 10$. Details of comparison between GADGET-3 and Enzo runs are given in Luo *et al.* (2016) and of the long-term evolution of SMBH seeds using sink particle technique in Shlosman *et al.* (2016). Collapse with the FLD in isolated halos is discussed in Luo *et al.* (2018) and in the cosmological context in Ardaneh *et al.* (2018). Runs with an adiabatic equation-of-state have been performed for comparison.

The FLD RT models demonstrate formation of the core with penetrating accretion streams, driving internal turbulence. Thermalization of the kinetic energy under the photosphere leads to the formation of hot bubbles, and drives convection. The density stratification in the core is weak, and the photosphere is far from being spherical. Strong anisotropic outflows mixes with the accretion flow. Figure 1 displays the evolution of gas density distribution in the innermost collapsing flow with superposed velocity vectors (Ardaneh *et al.* 2018). Expanding shells and hot bubbles form due to the radiation pressure generated by the core, which radiates intermittently near the Eddington limit with photospheric luminosities of $\sim 10^{38} - 10^{39}\,\mathrm{erg\,s^{-1}}$.

These features differ substantially from previous works which applied the adiabatic approximation in the optically-thick core. We confirm that the runs with adiabatic approximation lead to the formation of a central disk with spiral arms. Fragments are formed along the spiral shocks due to the Kelvin-Helmholtz shear instability and not the Jeans instability. Whereas with the FLD, the accreting gas is far less dominated by angular momentum, at least initially. The photosphere forms at a few AU, within which the gas becomes ionized and expands. At the end of the run, the central gas density has reached $10^{-6}\,\mathrm{g\,cm^{-3}}$ and the temperature increased to $\sim 10^{4.5}$ K. The mass accretion rate fluctuates between $0.1{-}1\,\mathrm{M_\odot\,yr^{-1}}$. Powerful recurrent outflows compete with the accretion flow and can lead to dissolution of the core or saturate its growth.

In the future we will attempt to run the RT simulation for a longer time to examine the long-term evolution of DC cores, and extend our work to Lyα emission and its impact on gas dynamics.

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