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The Dynamics of Seed Black Holes in the First Galaxies

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ABSTRACT

Copied from AAS. Should be updated before submission with main results. The discovery of bright quasars at redshift $z \geqslant 6$ in the Sloan Digital Sky Survey implies that black holes (BHs) as massive as $10^9 M_\odot$ were already assembled within 1 Gyr. Generically, these SMBHs are thought to have assembled by mergers with other BHs and by gas accretion onto less massive seed BHs. One candidate of such seed BHs are Population III (Pop III) stellar remnants. In order to map out plausible scenarios such massive objects form from Pop III remnants, we run a cosmological adaptive refinement mesh simulation of an overdense region of about 300 Mpc^3, which forms a few $10^9 M_\odot$ dark matter halos and over 13000 Pop III stars by redshift 15. Then we focus on one of these massive halos, containing 20 Pop III stellar remnants, to study the dynamical behavior of these BH seed candidates. Here we report on the evolution of the orbital properties of stellar-mass seed BHs in one of the first galaxies. They are distributed throughout the halo, creating a swarm of BHs, gradually falling toward the halo center through dynamical friction. From these characteristics, we estimate the BH merger rate in this particular galaxy, which is an important quantity to assess during the early buildup of massive BHs.

Key words: galaxies: formation – galaxies: dwarf – galaxies: high-redshift – methods: numerical

1 MOTIVATION

Since the discovery of bright quasars by Sloan Digital Sky Survey(SDSS) at high redshift($z \geqslant 6$), accretion onto super massive black holes(SMBHs) in the center (Fan et al 2006) is believed to be the only feasible power supply for some of the most luminous objects. If the accretion is at or below Eddington rate, the black holes must be as massive as 10^9M$_\odot$(Willott et al. 2003), which indicates that such massive objects were in place already when the universe was less than one billion years old. How such massive BHs formed within such a short period of time is still an open question. They must form early on and grow very rapidly through accretion and/or merger(Haiman&Loeb 2001). Simple estimation shows that if the "seed" BH has an inital mass of 1M$_\odot$, it has to accrete at or above Eddington rate during its entire lifetime(Volonteri&Bellovary 2012). Given feedback effects must exist to power the quasar, this scenario is extrmely unlikely, if not impossible. It will be more favorable if the seed BHs have an "intermediate" intial mass, e.g. between $100 - 10^5$M$_\odot$ (Volonteri&Bellovary 2012). The remnants of the very first generation of stars(Pop III stars), is considered as a promising candidate that falls in this category(Madau & Rees 2001).

(More references to be filled in here to summarize other work down this line. . .)

It is then natural to investigate the formation of seed BHs from Pop III remnants in a fully cosmological background, which is the emphasis of this paper. We first do a stacked analysis on a cosmological simulation presented in Xu et al.(2013), which has relatively large survey volume, for spatial distribution and orbital properties of seed BHs candidates. Then we run a zoom-in simulation based on the previous simulation for a high temporal analysis focusing on one single massive halo. In order to estimate seed BHs merger rate in first galaxies, we also perform a simulation with the same physics, much higher output frequency(1000 data sets) and thus smaller survey volume ((1Mpc)^3) due to limited computational power.

2 METHODS

2.1 Simulation Setup

Our analysis starts from the "Rarepeak" simulation conducted by Xu et al. (2013) that focuses on the frist stars and galaxies in an overdense region with $\langle\delta\rangle \equiv \langle\rho\rangle/(\Omega_M \rho_c) - 1 \simeq 0.65$ at $z = 15$ in the volume of 135 comoving Mpc^3, where Ω_M is the density of matter in units of critical density $\rho_c = 3H_0^2/8\pi G$. The simulation is performed with the adaptive mesh refinement(AMR)

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cosmological hydrodynamics code *Enzo* (Bryan et al. 2014). Radiation transport of ionizing photons are tracked by the adaptive ray tracing module *Moray*, which is coupled to the hydrodynamics, energy and chemistry solvers in *Enzo*. We have studied the number of Pop III remnants in the first galaxies(Xu et al. 2013), their contribution to the X-ray background(Xu et al. 2014). In this paper, we focus on the evolution of seed black holes(BHs) formed from these Pop III remnants. Here we give an overview of the simulation setup and numerical methods. A more detailed description of the star formation and feedback models are given in Wise et al. (2012a, 2012b) and Xu et al.(2013).

MUSIC(Hahn&Abel 2011) is used to generate the initial condition for the simulation at $z = 99$. The cosmological parameters are adopted from the 7-year *Wilkinson Microwave Anisotropy Probe*(WMAP) ΛCDM+SZ+LENS best fit (Komatsu et al. 2011):$\Omega_M = 0.266$, $\Omega_\Lambda = 0.734$, $\Omega_b = 0.0449$, $h = 0.71$, $\sigma_8 = 0.81$, and $n = 0.963$, where the variables have the usual definitions. We use a comoving simulation volume of $(40\text{Mpc})^3$ that has a 512^2 root grid resolution and three initial nested grids each with mass resolution eight times higher in each nested grid, which corresponds to an effective inital resolution of 4096^3 and dark matter(DM) mass resolution of $2.9 \times 10^4 \text{M}_\odot$. The comoving voulme of a finest nested grid is $5.2 \times 7.0 \times 8.3\ \text{Mpc}^3 (302\ \text{Mpc}^3)$. Further refinement in the Lagrangian volume of the finest nested grid is allowed up to a maximum AMR level $l = 12$, giving a maximal spatial resolution of 19 comoving pc. Refinement occurred when either a baryon or DM overdensity of $4 \times \Omega_{\{\text{b,DM}\}} \rho_c N^{l(1+\phi)}$, where $N = 2$ is the refinement factor , and $\phi = -0.1$ allows more aggressive refinement at higher densities, i.e., super-Lagrangian behavior. At $z = 15$ where the simulation ends, we have a large number (1000) of halos with $M > 10^8 \text{M}_\odot$, three of which with $M > 10^9 \text{M}_\odot$, in the Lagrangian region with a comoving volume of $3.8 \times 5.4 \times 6.6 \text{Mpc}^3 (135 \text{Mpc}^3)$. At this point, new formation of Pop III stars delines rapidly while the formation rate metal-enriched stars continues to increase. Pop III and metal-enriched stars have different formation and feedback models, distinguished by the total metallicity of the densest star-forming cell. The former are formed if [Z/H] < -4, and the latter are formed otherwise. The star formation and feedback models are the same as the "RP" simulation in Wise et al.(2012a), except that the characteristic mass $M_{char} = 40 \text{M}_\odot$ of the Pop III inital mass function(IMF), whereas Wise et al. used $100 \text{M}_\odot$. The Pop III stellar masses are randomly sampled from an IMF

$$f(\log M) dM = M^{-1.4} \exp\left[-\left(\frac{M_{char}}{M}\right)^{1.6}\right] dM \tag{1}$$

that behaves as a power-law IMF at $M > M_{char}$ and is cutoff exponentially below that mass(Chabrier 2003). Latest results of Pop III stars formation simulation shows that choosing M_{char} this way is more consistent(e.g. Turk et al. 2009; Greif et al. 2011; Hriano et al. 2013; Susa 2013; Susa 2014). Metal-enriched star formation is modeled as in Wise & Cen(2009), which is similar to the Pop III prescription without the requirement of minimum H_2 fraction. This requirement is not valid in this case because the metal-enriched gas can efficiently cool even in the presence of a strong UV radiation field(e.g. Safranek-Shrader et al. 2010). Star formation is restricted to cold gas, with temperatures $T < 1000K$. Pop III star particles represent individual stars, whereas metal-enriched star particles represent a star cluster of some total mass and an presumed normal (i.e., Kroupa) IMF minimum and maximum stellar masses inferred in the Milky Way. The minimum mass of a star particle is set to $m_{\star,min} = 1000 \text{M}_\odot$. The star particle does not provide any and continues to accrete until it reaches $m_{\star,min}$.

2.2 Orbital Elements

*approximation: key orbital properties of seed BHs: semi-major axes and eccentricities
*calculation of semi-major axis and eccentricities
*Angular momentum and estimation of merger rate by the evolution.

3 RESULTS

3.1 Stacked Analysis

Radial distribution of seed BHs at different stages:
Orbital properties:

3.2 Case Study: High Temporal Analysis of a Single Galaxy

Seed BHs position: Angular momentum evolution:

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