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MESA-QUEST: Modeling Quasi-Stars in MESA

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ABSTRACT

Supermassive black hole formation remains an unsolved problem. Quasi-stars have been suggested as a viable heavy-seeding mechanism. In this work, we implement methods for modeling quasi-stars previously used with the Cambridge STARS code into the 1D stellar evolution code Mesa. The computational capabilities of Mesa allow for more detailed simulations of quasi-star evolution due to its modularity and the ease of implementing of new physical processes and controls. Our implementation, the MESA QUasi-star Evolutionary Simulation Toolkit (MESA-QUEST), is available in a publicly accessible repository.

Keywords: supermassive black holes (1663) — black holes (162) — stellar evolutionary models (2046)

1. INTRODUCTION

Recent JWST observations of early-universe supermassive black holes (SMBHs), such as the $\sim 4 \times 10^7$ $M_\odot$ quasar in UHZ1 (P. Natarajan et al. 2023), motivate work studying their early-time formation pathways. Direct collapse, which can occur when a massive cloud of low-metallicity pre-galactic gas monolithically collapses to form a central black hole, may be a viable means of seeding SMBHs (M. C. Begelman et al. 2006). This may be observable as a 'quasi-star', a hypothetical star-like object where an extended spherical envelope of gas is supported by the central black hole's accretion luminosity rather than nuclear fusion (*e.g.* M. C. Begelman et al. 2008).

Previous works have computationally modeled quasi-stars to determine their observable properties and evaluate their potential as a mechanism to seed SMBHs (W. H. Ball et al. 2011; W. H. Ball 2012; E. R. Coughlin & M. C. Begelman 2024). In this work, we develop new capabilities for simulating quasi-star models using the 1D stellar evolution code Mesa (B. Paxton et al. 2011). We are motivated to extend Mesa because it is an open-source, up-to-date stellar evolution code with a wide variety of pre-existing capabilities. Mesa's capabilities enable us to more easily include physical processes absent from past simulations such as envelope accretion, mass-loss from winds, and photon-trapping. This requires a number of changes to the code itself and adjustments of the input parameters within Mesa, which we discuss in the following sections. We validate our Mesa implementation by reproducing the fiducial models from W. H. Ball et al. (2011).

Our code and examples are available in a public repository.[3] All new physics are implemented in the *run_star_extras* file. The provided *inlist_project* will simulate the model shown in Fig. 1. The *x_ctrl* and *x_logical_ctrl* parameters within this file control dimensionless efficiency parameters.

2. IMPLEMENTATION

Our implementation follows from the methods introduced in W. H. Ball et al. (2011) and W. H. Ball (2012). We treat the central black hole as a point mass at the origin. To prevent singularities, we adjust the center-most point of the simulation to r_0, beyond the Schwarzschild radius of the black hole. The mass contained within the sphere of radius r_0 is M_0, including the black hole and some infalling mass. These changes are given by

$$r_0 = r_B = \frac{2GM_{\rm BH}}{c_s^2}, \tag{1}$$

$$M_0 = M_{\rm BH} + M_{\rm cav}, \tag{2}$$

where r_B is the central black hole's Bondi radius, $M_{\rm BH}$ is the mass of the black hole, c_s is the core speed of sound, and $M_{\rm cav}$ is the mass contained within the in-

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[3] http://www.github.com/andysantarelli/MESA-QUEST

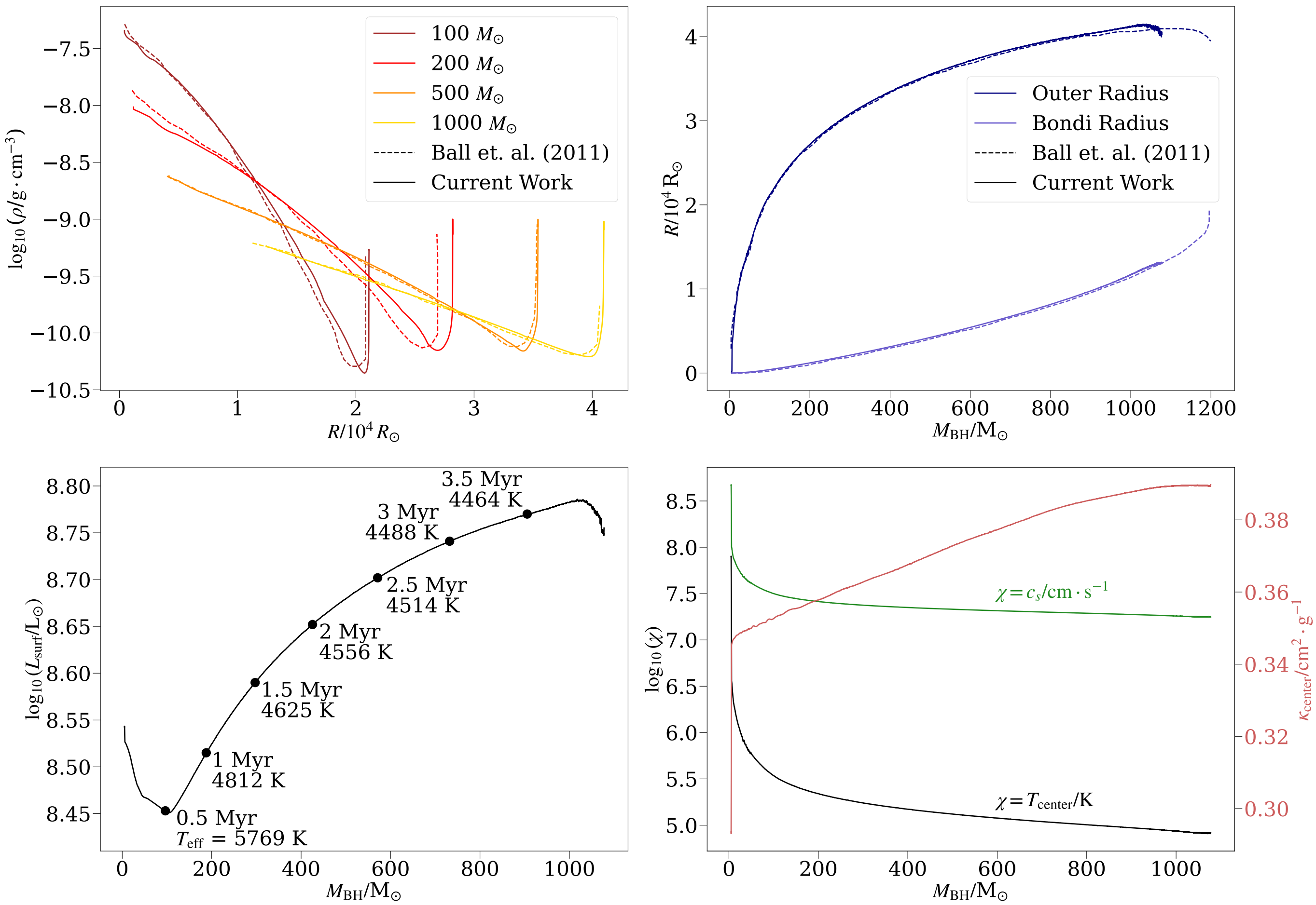

Figure 1. **Mesa and Ball (2011) Comparison:** (Top) Density as a function of radial profile (left) and outer and Bondi radius as a function of black hole mass (right) from W. H. Ball et al. (2011) (dashed) and our fiducial Mesa model (solid) using $(\epsilon, \eta) = (0.1, 0.1)$. For the density, these profiles are chosen to match available data from W. H. Ball et al. (2011) and are not evenly spaced in time. (Bottom) Surface (left) and core (right) properties of our quasi-star as functions of black hole mass, including model ages.

ner boundary radius and comes from the estimation of the density profile where $\rho \propto r^{-3/2}$. With these adjustments, Mesa now integrates the equations of stellar structure outward from r_0 and M_0 rather than 0.

The accretion rate and the corresponding convectively-limited luminosity are given by

$$\dot{M}_{\rm BH} = 16\pi \frac{\eta}{\epsilon\Gamma} \frac{(GM_{\rm BH})^2}{c_s c^2} \rho \tag{3}$$

$$L_{\rm BH} = \frac{\epsilon}{1-\epsilon} \dot{M}_{\rm BH} c^2 \tag{4}$$

where η and ϵ are the convective and radiative efficiencies respectively, both taken to be 0.1, and Γ is the adiabatic index which is evaluated self-consistently within Mesa. This results in a luminosity close to the Eddington limit for the entire star such that

$$L_{\star,\rm Edd} = 4\pi \frac{c}{\kappa} G M_\star. \tag{5}$$

Extreme conditions surrounding the BH result in data noise close to r_0 when solving equations of stellar structure, so we average the sound speed across the innermost 50 zones (< 1% of the object by mass). For our fiducial models below we substitute the default mixing length theory in Mesa for that of E. Böhm-Vitense (1958), denoted 'ML1', to match the methods of W. H. Ball et al. (2011).

Due to their high masses and core densities, quasi-stars are prone to the general relativistic instability and thus require corrections to account for these effects (N. P. Herrington et al. 2023). This is handled in Mesa by applying the Tolman-Oppenheimer-Volkoff correction to the equation of hydrostatic equilibrium. We implement this through the *run_star_extras* file, where Mesa applies the correction to each zone at every timestep. Additionally, we implement the Ledoux criterion for convective stability, using the default semiconvective mixing efficiency parameter (N. P. Herrington et al. 2023).

To verify Mesa's capability to simulate quasi-stars, we compare our model to the fiducial model in W. H. Ball et al. (2011), modeled in the Cambridge STARS code (P. P. Eggleton 1972). In Fig. 1 we show the density profiles of our model as the central black hole grows (top left) and the position of the inner radius r_0 and the outer radius of the star (top right). Our model reaches a final BH mass within 10% of the W. H. Ball et al. (2011) model and follows a similar structural evolution. The surface luminosity (bottom left) grows steadily with age while the surface temperature gradually declines. The core conditions (bottom right) are numerically stable.

3. CONCLUSIONS

We have developed new capabilities for Mesa to simulate quasi-stars and demonstrated consistency with the literature. This will allow us to easily include previously omitted processes in our future work, such as mass loss from winds and mass gain from envelope accretion, to better determine the circumstances in which quasi-stars form heavy seeds. As Mesa is open source, it is straightforward to adapt our code to run with new accretion schemes that have been developed in recent years, which will be studied in future work.

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