


Evolutionary Tracks and Spectral Properties of Quasi-stars and Their Correlation with Little Red Dots

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ABSTRACT

JWST has revealed a population of red, compact, high-redshift ($z \sim 3 - 10$) objects referred to as “Little Red Dots” (LRDs). These objects exhibit unusual spectral features reminiscent of stellar spectra with blackbody-like SEDs, **large hydrogen Balmer breaks**, **Balmer line absorption**, and **classical stellar absorption features such as calcium H&K and the calcium triplet**. Following the recent suggestion that these may be actively accreting direct-collapse black holes in the process of assembly, *i.e.* quasi-stars, we present evolutionary models of quasi-stars using our recently released, publicly available MESA-QUEST modeling framework. We compute a grid of models spanning a range of black hole masses and predict the luminosities, temperatures, surface gravities, and lifetimes of these objects. We find that these models lie along a Hayashi track once they hit their “late-stage” which constitutes the majority of their lives (~ 20 Myr). We present scaling relations for estimating the mass of a quasi-star as a function of the bolometric luminosity, as well as the bolometric luminosity as a function of the effective temperature for the Hayashi track. The short lifetimes in tandem with the observed number density of LRDs imply the possibility that every supermassive black hole was once a quasi-star. We compare synthetic spectra of our quasi-star models to observations of LRDs, and show that these models are broadly capable of reproducing the continuum spectra of observed LRDs. These results indicate that quasi-stars are promising candidates for the origin of supermassive black holes via direct collapse in the early universe.

Keywords: Black holes (162) — Supermassive black holes (1663) — Stellar evolutionary models (2046)
— Galaxies (573) — Active galactic nuclei (16)

1. INTRODUCTION

The rapid emergence of supermassive black holes (SMBHs) within the first ~ 700 Myr of cosmic history remains a major puzzle. Observations indicating black hole-to-stellar mass ratios up to $\sim 10\%$, significantly higher than those observed locally (Y. Harikane et al. 2023; B. L. Jones et al. 2025; R. Maiolino et al. 2025; M. Yue et al. 2024), suggest that the theoretically proposed “direct collapse” pathway for forming massive initial black hole seeds may have been in operation in the

early Universe (D. J. Whalen et al. 2023; P. Natarajan et al. 2024; E. R. Coughlin & M. C. Begelman 2024). In this scenario, a heavy seed black hole of order $10^4 M_{\odot}$ forms from the gravitational collapse of low metallicity gas in early-universe dense pre-galactic gas clouds in various cosmic settings, which then accretes at the Eddington limit until it fully forms a SMBH (M. G. Haehnelt & M. J. Rees 1993; A. Loeb & F. A. Rasio 1994; D. J. Eisenstein & A. Loeb 1995; P. Madau & M. J. Rees 2001; V. Bromm & A. Loeb 2003; G. Lodato & P. Natarajan 2006; M. C. Begelman et al. 2006; P. Natarajan et al. 2017) or from the rapid amplification of a light initial seed that can grow at super-Eddington

rates (B. Devecchi & M. Volonteri 2009; L. Mayer et al. 2010; T. Alexander & P. Natarajan 2014).

The evolution of direct collapse heavy seed formation is expected to proceed in the form of a quasi-star (G. Lodato & P. Natarajan 2006; M. C. Begelman et al. 2008). These are formed when the core of either a super-massive star or a pre-galactic gas cloud directly collapses initially into a stellar mass black hole around which the remaining gas is assembled as an envelope. This envelope around the growing black hole seed is then supported by the radiation pressure produced from accretion onto the black hole, which can rapidly accrete at super-Eddington rates due to the efficient transport of energy via convection and jets, allowing the central black hole to accrete at roughly the Eddington limit of the entire quasi-star (M. C. Begelman et al. 2006, 2008; M. C. Begelman 2010; W. H. Ball 2012a; D. Fiacconi & E. M. Rossi 2015; C. B. Campbell et al. 2025).

Among the high-redshift, actively-accreting black hole observations by JWST are a subset of candidate active galactic nuclei (AGN) that have come to be known as “Little Red Dots” (LRDs) – high-redshift, morphologically compact, ultra-luminous objects with unique spectral characteristics (J. Matthee et al. 2024; J. E. Greene et al. 2024; I. Labbe et al. 2025; H. B. Akins et al. 2024; I. Juodžbalis et al. 2024; V. Kokorev et al. 2024; D. D. Kocevski et al. 2025; Hviding, Raphael E. et al. 2025; X. Ji et al. 2025; A. J. Taylor et al. 2025). These objects exhibit an unusually strong Balmer break as well as an extended, flat spectrum in the near-infrared (NIR). The combination of these features, in addition to a blue UV slope, results in a unique “V”-shaped spectral energy distribution (SED, G. Barro et al. 2024; Killi, Meghana et al. 2024; de Graaff, Anna et al. 2025; D. D. Kocevski et al. 2025; I. Labbe et al. 2023).

Currently, there is no complete explanation for what these LRDs are composed of and hence their unique signatures. The relative contributions of emitted flux originating from star formation versus accretion onto a central BH are debated. Several studies suggest that LRDs are black holes embedded in dense gas, with R. P. Naidu et al. (2025) dubbing their model a “black hole star” (e.g., de Graaff, Anna et al. 2025; K. Inayoshi & R. Maiolino 2025; X. Ji et al. 2025; D. Kido et al. 2025; H. Liu et al. 2025; A. J. Taylor et al. 2025). This is motivated by their nearly blackbody-like SEDs, prominent hydrogen Balmer breaks, Balmer line absorption, and classical stellar absorption features such as Ca H&K and the Ca II triplet, which are consistent with emission from an optically thick, thermally emitting envelope surrounding an accreting black hole. J. Jeon et al. (2025) further proposed that LRDs could be remnants of direct

collapse, consistent with the quasi-star scenario (M. C. Begelman et al. 2006, 2008; M. C. Begelman 2010), and M. C. Begelman & J. Dexter (2025) have argued that they would most likely represent the “late stage” of this process where the BH has accreted at least 10% the total mass of the system.

Thus far, there has been no comparison between quasi-star evolutionary models and JWST’s LRDs. In this work, we present simulations of quasi-star evolution using MESA (B. Paxton et al. 2011, 2013, 2015, 2018, 2019; A. S. Jermyn et al. 2023) and the MESA-QUEST modeling framework (C. B. Campbell et al. 2025; A. D. Santarelli et al. 2025). We extract spectral predictions to compare with recent JWST observations of two LRDs: MoM-BH*-1 (R. P. Naidu et al. 2025) and UNCOVER-45924 (I. Labbe et al. 2024). We compare our predictions with observations for both a quasi-star by itself and a quasi-star embedded within a star-forming galaxy, akin to the scenario predicted by P. Natarajan et al. (2017). We also consider simple corrections for dust attenuation, but find little evidence for it, in line with recent findings that dust attenuation in LRDs may be subtle or negligible (C. M. Casey et al. 2025; de Graaff, Anna et al. 2025; R. P. Naidu et al. 2025; D. J. Setton et al. 2025; Xiao, Mengyuan et al. 2025). We find that our fiducial $10^6 M_{\odot}$ quasi-star model broadly reproduces the continuum spectra of these LRDs, thereby lending evidence that SMBHs may assemble by passing through the direct-collapse quasi-star phase.

The outline of our paper is as follows: in Section 2, we provide details of how we extract spectra from quasi-star models in MESA-QUEST. We present the results from models and comparisons with observational data of two JWST LRDs in Section 3, and close with a final discussion and implications of these results.

2. METHODS: EXTRACTING QUASI-STAR SPECTRA FROM MESA-QUEST

In this section, we briefly outline our quasi-star MESA models. We use our previously developed framework MESA-QUEST, which includes several newly implemented upgrades: flexible inner boundary conditions, accretion schemes, and improvements that enable modeling higher total masses than previously studied. The following section briefly outlines these methods; more details can be found in A. D. Santarelli et al. (2025) and C. B. Campbell et al. (2025). We note that all MESA models and plotting scripts are publicly available via the MESA-QUEST Github repository.⁸

⁸ <http://www.github.com/andsantarelli/MESA-QUEST>

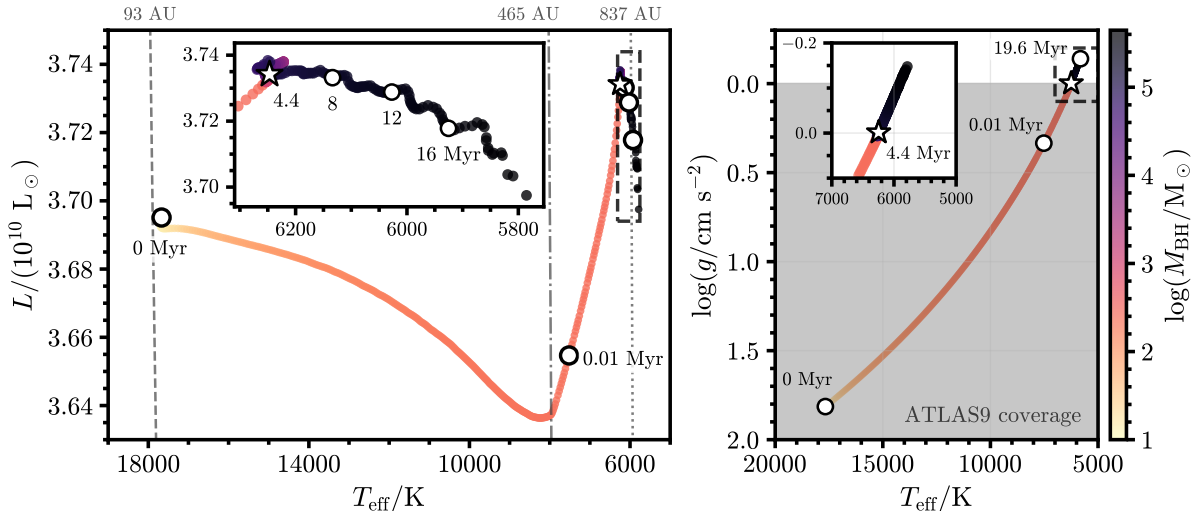


Figure 1. Evolution of a theoretical quasi-star model in Hertzsprung-Russell (left) and Kiel (right) diagrams with initial parameters $M_{\text{BH}} = 10 M_{\odot}$, $M_{\star} = 10^6 M_{\odot}$, and $Z = 0$. After an initial contraction phase lasting ~ 0.1 Myr, the model spends the remainder of its lifetime (~ 20 Myr) at $\sim 3.72 \cdot 10^{10} L_{\odot}$ and ~ 6000 K before becoming a $\sim 10^6 M_{\odot}$ SMBH. Black hole mass is shown with a color gradient. Lines of constant radius are shown in gray, labeled above the top axis. Note that while these lines appear vertical, this is simply due to the small luminosity range. The gray region in the Kiel diagram represents the $\log(g)$ - T_{eff} space covered by the ATLAS9 atmosphere models. The star represents the beginning of the quasi-star’s late-stage, approximately where the luminosity peaks on the HR diagram and where it spends the majority of its life.

2.1. Quasi-star Modeling

A quasi-star is modelled as black hole enveloped within a star via an adjustment to the inner boundary conditions of the stellar structure equations such that:

$$m(r_0 = R_{\text{in}}) = M_{\text{BH}} \quad (1)$$

$$l(r_0 = R_{\text{in}}) = L_{\text{BH}} \quad (2)$$

where r_0 is the innermost grid point, R_{in} is the updated inner boundary, and M_{BH} and L_{BH} are the black hole mass and accretion luminosity respectively. In this work, we use the “saturated-convection” radius, the boundary within which material is slowly drifting inward while convection transports energy outward at the highest possible rate (E. R. Coughlin & M. C. Begelman 2024). Details on the calculation of this boundary can be found in E. R. Coughlin & M. C. Begelman (2024), with further implementation details in A. D. Santarelli et al. (2025) and C. B. Campbell et al. (2025). For the accretion luminosity, and thus the accretion rate, we use the Eddington limit of the entire object such that

$$L_0 = \alpha L_{\text{E}} = \alpha 4\pi \frac{c}{\kappa} GM_{\star} \quad (3)$$

$$\dot{M}_{\text{BH}} = \frac{1 - \epsilon}{\epsilon} \frac{4\pi}{\kappa c} \alpha GM_{\star}. \quad (4)$$

Previous works modeling the accretion and resulting luminosity report only a factor of < 2 deviation from the

object’s Eddington limit throughout the quasi-star’s lifetime (W. H. Ball 2012b; C. B. Campbell et al. 2025). The dimensionless scaling factor α serves as a proxy for a range of physical effects that enhance or suppress accretion such as rotation, magnetic fields, photon-trapping, etc., which we plan to implement and explore more thoroughly in future work. Here we adopt a simple scaling factor α and use $\alpha = 1$ as a first approximation.

Fig. 1 shows a detailed single evolutionary track for a $10^6 M_{\odot}$ total mass quasi-star with an initial BH mass of $10 M_{\odot}$ and metallicity $Z = 0$. The timescale of the initial tail is short and comparable to the Kelvin-Helmholtz timescale,

$$t_{\text{KH}} \simeq 0.04 \text{ Myr} \left(\frac{M}{10^6 M_{\odot}} \right)^2 \left(\frac{R}{2 \cdot 10^4 R_{\odot}} \right)^{-1} \left(\frac{L}{3.7 \cdot 10^{10} L_{\odot}} \right)^{-1} \quad (5)$$

after which the quasi-star “settles” as the black hole mass reaches $\sim 10^3 M_{\odot}$. The inset plot shows the majority of the quasi-star’s life as it dims and cools.

The final age of this model is ~ 20 Myr, though the actual lifetimes may be longer as our models do not currently indicate what happens once the inner boundary condition exceeds the total radius. If we assume that BH growth continues at a similar rate until the entire object is consumed, we expect a total lifetime of 30 – 40 Myr.

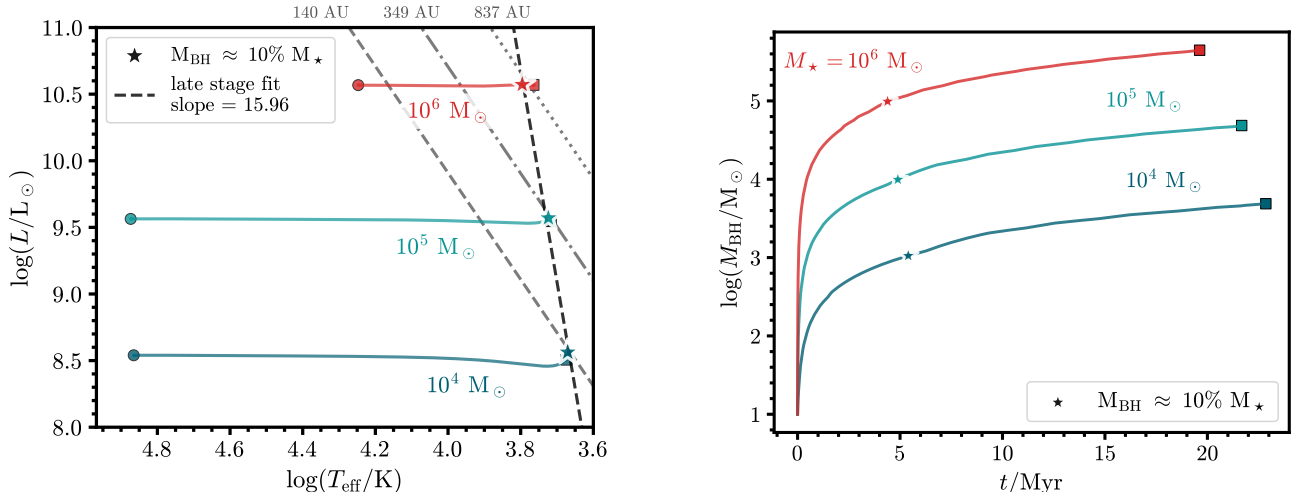


Figure 2. Evolution of three quasi-stars with masses $10^4 M_{\odot}$ (blue), $10^5 M_{\odot}$ (green), and $10^6 M_{\odot}$ (red). A Hertzsprung-Russell diagram is shown on the left, and the black hole mass growth with age on the right. The start and end points in the HR diagram are marked with circles and squares, respectively. The beginning of the late-stage period tracing a Hayashi track is shown with star symbols, and the fit is depicted with a black dashed line. Lines of constant radius are shown in gray and labeled above the top axis.

We show evolutionary tracks for multiple masses in Fig. 2, including a line marking where the quasi-star models enter their “late stage” i.e. $M_{\text{BH}}/M_{\star} = 0.1$. Due to the large accretion luminosity and high opacity, the envelope becomes fully convective and the model evolves to low effective temperatures and hence occupies the Hayashi track — the hydrostatic limit for such structures — for most of its lifetime, akin to fully convective pre-main-sequence stars and red giants with deep convective envelopes. The fit for their Hayashi track can be reasonably well represented by

$$\log(L/L_{\odot}) = 16 \log(T_{\text{eff}}/K) - 50. \quad (6)$$

One can in principle also obtain an estimate for the mass of an observed quasi-star based on its luminosity through Eq. 3 via

$$M_{\star} \simeq 10^6 M_{\odot} \left(\frac{L}{3.7 \cdot 10^{10} L_{\odot}} \right) \quad (7)$$

where for convenience we have dropped the dependency on κ and α , though we note that their variation can have a large influence on the accretion physics and thus the luminosity itself (A. D. Santarelli et al. 2025).

2.2. Extracting Synthetic Spectral-Energy Distributions

In order to extract the synthetic spectra of quasi-stars, we use the MESA colors module, developed by N. J. Miller (2025). This is a built-in tool within MESA that

can be used to generate synthetic spectral-energy distributions (SEDs) by sampling the nearest grid point in a stellar atmosphere model grid using the stellar surface conditions output by MESA (i.e. T_{eff} , $\log(g)$, and metallicity Z). Furthermore, colors can then convolve these synthetic SEDs with filter transmission curves from astronomical surveys including *Gaia* and *JWST*, the latter of which we use in this work.

We use the ATLAS9 atmospheric model grid (F. Castelli & R. L. Kurucz 2003), the data and interpolation for which is provided by default in the colors module. However, it should be noted that this grid does not span the full parameter space to cover that of quasi-stars at all points in their lifetimes. Fig. 3 shows a Kiel diagram containing points for various quasi-star models. The small gray region shows the $\log(g) - T_{\text{eff}}$ space covered by the ATLAS9 grid. Although all model temperatures lie firmly within the grid range, many of the quasi-star models lie outside of the $\log(g)$ range. Furthermore, the lowest metallicity provided is $[\text{Fe}/\text{H}] = -5$. This leaves only the $10^6 M_{\odot}$, $[\text{Fe}/\text{H}] = -4$ quasi-star evolutionary model that fits within the atmosphere grid. However, comparison of the low and zero metallicity models shows very little difference in the final SEDs, and therefore we use a $10^6 M_{\odot}$, $Z = 0$ model for all SEDs in this work.

A few caveats arise due to our adoption of the ATLAS9 atmosphere models. First, these models are computed in local thermodynamic equilibrium (LTE) and therefore lack the physics necessary to produce all of the

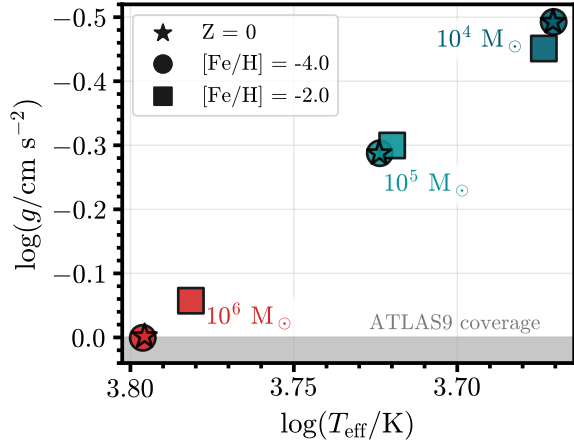


Figure 3. A set of quasi-star models at $M_{\text{BH}} \approx 0.1M_{\star}$, which is the point at which the quasi-star has reached what we consider the “late-stage” where it remains predominantly static within the HR diagram. The gray shaded region indicates the space covered by the ATLAS9 grids. Additionally, these grids span $-5 \leq [\text{Fe}/\text{H}] \leq 1.5$.

emission lines required for rigorous analysis. Additionally, a solar-scaled abundance mixture is assumed, and thus absorption features that would not otherwise be present in metal-free atmospheres are seen. This primarily appears in our models at the H and K singly-ionized calcium (CaII) lines at 3968 Å and 3934 Å respectively. While these strong absorption features are present in the adopted ATLAS9 atmosphere models, they can safely be ignored in this work as there is little to no Ca present in the atmospheres of our quasi-star models, and are expected to be far less abundant in the composition of the gas at the high redshifts studied in this work. It is however conceivable that quasi-stars may have some enrichment via accretion onto the envelope from a host galaxy that has undergone some star formation. We emphasize again that our comparisons are between the continuum features of the models and observations and serve as a pilot study. The modeling and implementation of more detailed atmosphere models will be the subject of future study.

2.3. Host Galaxy & Dust Corrections

Multiple explanations for the observed LRD spectra have been proposed. Leading theories are that these are compact, luminous objects (such as a quasi-star or black hole star) with additional components in the emission deriving from host galaxies or dust, although dust is presently disfavored (de Graaff, Anna et al. 2025; I. Labbe et al. 2024; R. P. Naidu et al. 2025; D. J. Setton et al. 2025). Observations are presently inconclusive

with regard to the issue of the contribution to the flux from the stellar component of the host galaxies. Additionally, dust properties may vary between sources and with redshift, so we remain agnostic when exploring the impact of the stellar population of a host galaxy and dust to our models.

In order to combine our quasi-star model with that of its host galaxy, we use spectral data from the Dawn JWST Archive (DJA, de Graaff, Anna et al. 2025; K. E. Heintz et al. 2024; F. Valentino et al. 2023). We create semi-synthetic models by simply combining our theoretical model with an observed star-forming galaxy at a redshift similar to the observed LRD. The hosts we have selected (UNCOVER-24996 and MoM-UDS-948311) primarily contribute to the UV spectrum where they dominate, and are found at similar sky positions and redshifts to their respective LRDs ($z \simeq 7.7$ and $z \simeq 4.4$) (R. P. Naidu et al. 2024, 2025). In the quasi-star scenario, a host similar to those selected would serve as the ionizing source that prevents the fragmentation due to molecular hydrogen, thus enabling the formation of the quasi-star (B. Agarwal et al. 2013; B. Agarwal et al. 2016; M. C. Begelman et al. 2006; P. Natarajan et al. 2017; R. P. Naidu et al. 2025; J. A. Regan et al. 2017; C. Shang et al. 2010; E. Visbal & Z. Haiman 2018).

We implement dust corrections to our models using the simplified methods of S. Salim & D. Narayanan (2020) via

$$m_{\lambda} = m_{\lambda,0} + A_{\lambda} \quad (8)$$

where $m_{\lambda,0}$ is the dust-free model (i.e. the quasi-star on its own) and A_{λ} is the dust curve itself. Although there are several components that go into calculating A_{λ} , we use a simple case based only on the UV-optical slope S and a small UV-bump with strength B . In this work, we use optical depth $A_V = 1.6$ and bump strength $B = 0.1$. It should be noted that the effects of this bump strength are minimal and can be safely ignored if necessary, and that A_V values this high have been ruled out for several LRDs (D. J. Setton et al. 2025).

3. RESULTS

Here we compare the predicted spectra of a fiducial $10^6 M_{\odot}$ quasi-star model with JWST observations of two LRDs: UNCOVER-45924 and MoM-BH*-1 (I. Labbe et al. 2024; R. P. Naidu et al. 2025). We present the former as an example of a “typical” LRD and the latter as an example with an extreme Balmer break and only small contributions from a host galaxy. To facilitate this comparison, we normalize the flux at wavelengths corresponding to continuum features, and correct the wavelengths in the model and observations for the redshift in order to compare in the rest frame.

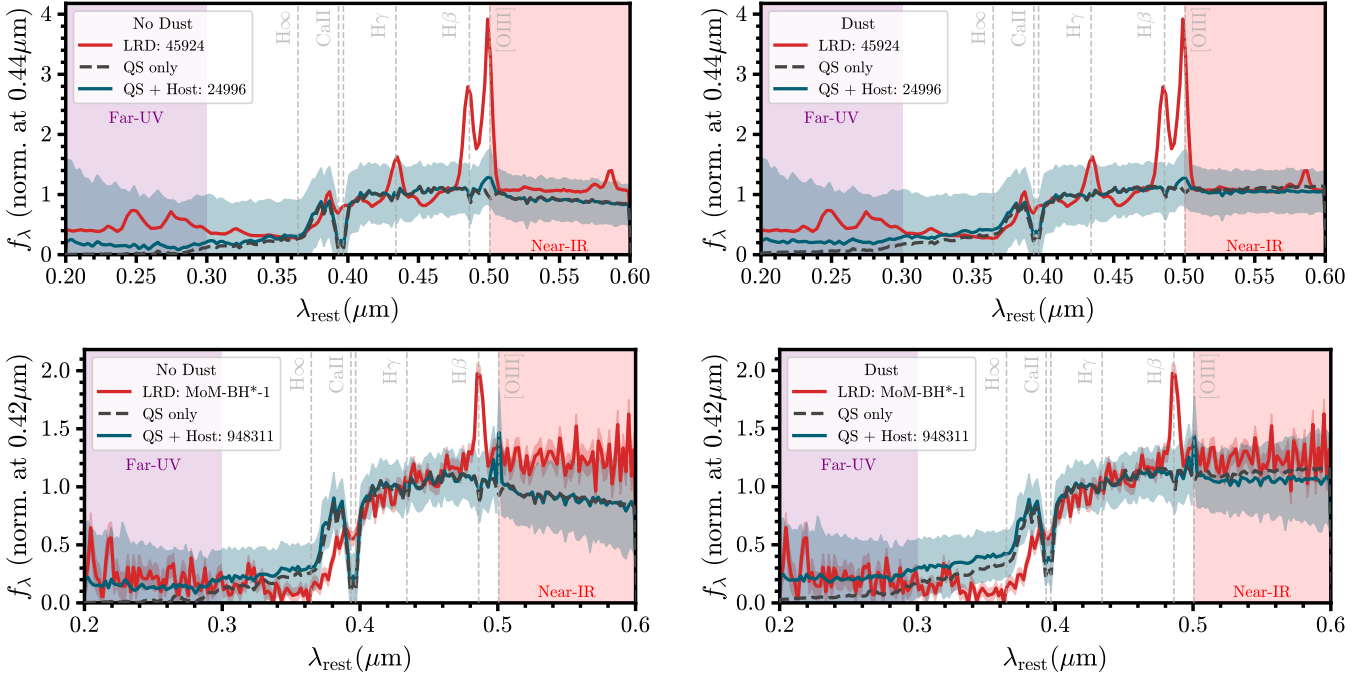


Figure 4. Predicted SEDs of a $10^6 M_{\odot}$ total mass, late-stage quasi-star both on its own (black dashed line) and embedded in a host galaxy (solid blue line) compared with JWST observations of LRDs (red) that includes the emission from the host stellar component with masses $\sim 10^{9.5} M_{\odot}$. The top row shows comparisons with UNCOVER-45924 (I. Labbe et al. 2024) and the bottom row with MoM-BH*-1 (R. P. Naidu et al. 2025). We show models with (left) and without (right) dust. Semi-synthetic models of quasi-stars embedded in a host galaxy are shown in blue, using hosts properties inferred for UNCOVER-24996 and MoM-UDS-948311 respectively. The faded colors surrounding the lines represent 1σ uncertainties in JWST measurements. Gray dashed lines indicate key wavelengths: the Balmer break ($H\infty$), $H\gamma$, $H\beta$, [OIII], and both CaII lines. Discrepancies in emission lines likely arise from the use of LTE atmospheres at nonzero metallicity, particularly in the $H\beta$ emission and CaII absorption lines - these are discussed in Sec. 2.2. Shaded regions indicate the far-UV and NIR approach, highlighting a few of the well fit continuum regions discussed in Sec. 3. The stellar parameters of the quasi-star model at this point are $T_{\text{eff}} = 6241 \text{ K}$, $\log(g) = -0.003$, and $Z = 0$.

Although this quasi-star model was not specifically fit to either LRD, it qualitatively reproduces the main continuum features seen in both. In order to make this comparison more quantitative, and despite the aforementioned limitations of our adopted atmospheric models which prevent detailed comparisons of individual spectral features, we compare the slopes of the UV and NIR-approach as well as the strength of the Balmer break. We find general agreement, with a few caveats listed below. Note that although the same quasi-star model is used for both comparisons, the different normalizations cause the model to have different values when compared to different sources.

For each of our configurations (i.e. a quasi-star with and without a host, each with and without dust), we calculate the UV and NIR-approach slope parameters β_{blue} , β_{red} (where $f_{\lambda} \propto \lambda^{\beta}$) by performing linear regression in log-log space over the rest-frame wavelength ranges $0.18\text{--}0.28 \mu\text{m}$ and $0.51\text{--}0.57 \mu\text{m}$, respectively. We then do the same for each LRD and compare the results. We find that the comparisons are in good agree-

ment ($< 2.5\sigma$) except in two cases, both of which are in the UNCOVER comparison with dust: with a host in the UV region (2.9σ) and without a host in the NIR-approach (3.6σ). This is concordant with other studies finding minimal evidence of dust attenuation in LRDs (D. J. Setton et al. 2025).

We calculate the Balmer break strengths using the mean flux in the wavelength windows of $3620\text{--}3720 \text{ \AA}$ and $4000\text{--}4100 \text{ \AA}$. For the UNCOVER source, our model yields a break strength of 3.97, closely matching the LRD’s value of 3.92 ± 0.03 . The value of the break in our model does not change significantly with the addition of a host galaxy, as the Balmer break window is dominated by the quasi-star flux. Although the far-UV portion of the standalone quasi-star is relatively weak, we obtain the characteristic LRD “V”-shape with the addition of a host galaxy. The inclusion of dust in the model slightly alters the fit by maintaining the NIR continuum. This modification has little effect, in agreement with recent claims that LRDs are mostly dust-free

(C. M. Casey et al. 2025; R. P. Naidu et al. 2025; D. J. Setton et al. 2025; Xiao, Mengyuan et al. 2025).

The other source, MoM-BH*-1, has one of the most pronounced Balmer breaks ($7.7^{+2.3}_{-1.4}$) of any LRD discovered (R. P. Naidu et al. 2025). While this is a more pronounced break than in our model (3.97), as noted previously, this comparison may improve significantly with the adoption of more appropriate atmosphere models. Furthermore, this comparison is with a fiducial $10^6 M_{\odot}$ quasi-star model not specifically fit to this source; a higher-mass model may reproduce these features more closely. Based on Fig. 1 we can estimate that a quasi-star model containing a more massive black hole of a few $\times 10^6 M_{\odot}$ will closely match the LRD’s bolometric luminosity. These topics will be the subjects of future investigations.

4. CONCLUSIONS & DISCUSSION

We have presented new MESA quasi-star evolutionary models generated with the MESA-QUEST framework and compared their synthetic spectra to JWST observations of LRDs. Our results demonstrate that late-stage quasi-stars, with black holes comprising $\gtrsim 10\%$ of their total mass and photospheric temperatures near 6000 K, naturally produce the defining continuum features of LRDs: large Balmer breaks, flat or red near-infrared slopes, and weak ultraviolet emission. These properties emerge self-consistently from the quasi-star’s radiation-supported envelope, and do not require an old stellar population or extreme dust reddening.

The quasi-star phase of direct collapse formation of heavy seed black holes offers a plausible solution to the rapid emergence of supermassive black holes within the first few hundred million years of the Universe. A population of short-lived ($\lesssim 20$ Myr), extremely luminous

quasi-stars could account for the high observed number density of LRDs, implying that early SMBHs may assemble by passing through this stage. Folding in lifetimes from our models along with predictions of progenitor cloud masses will allow us to predict if this is the case. Given the short lifetimes in our models, this can plausibly show that *all* SMBHs formed this way.

Our synthetic spectra are limited to LTE stellar-atmosphere approximations and therefore capture continuum but not emission-line physics; future non-LTE radiative-transfer models will be required to capture these additional features. Nevertheless, the present results establish quasi-stars as viable progenitors of both LRDs and the earliest supermassive black holes. If JWST’s LRDs indeed trace this brief phase, we may be witnessing the birth of supermassive black holes at cosmic dawn.

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