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Little Red Dots As Late-stage Quasi-stars

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ABSTRACT

We argue that the "Little Red Dots" (LRDs) discovered with the *James Webb Space Telescope* are quasi-stars in their late stages of evolution. Quasi-stars are hypothetical objects predicted to form following the core collapse of supermassive stars, and consist of black holes accreting from massive envelopes at a super-Eddington rate. We show that models of late-stage quasi-stars, with black hole masses exceeding $\sim 10\%$ of the total, predict thermal and radiative properties that are insensitive to both black hole and envelope mass, and spectrally resemble LRDs. Specifically, we show that they are likely to exhibit reddish colors, a strong Balmer break, and possess conditions favorable to the production of Balmer lines that are broadened by electron scattering. Their huge electron column densities suppress any X-rays. Late-stage quasi-stars, with black hole masses $\gtrsim 10^6 M_\odot$, should dominate the overall quasi-star population. Their short predicted lifetimes (tens of Myr), coupled with the high observed comoving density of LRDs, suggest that most or all supermassive black holes go through a quasi-star/LRD phase during their formation and growth.

Keywords: Accretion (14) — Active galactic nuclei (16) — High-redshift galaxies (734) — Quasars (1319) — Supermassive black holes (1663)

1. INTRODUCTION

Little Red Dots (LRDs) comprise a population of high-redshift objects discovered with the *James Webb Space Telescope* (*JWST*) that are characterized by a "V-shaped" spectrum in rest-frame UV-to-optical bands (Matthee et al. 2024; Greene et al. 2024; Kocevski et al. 2024; Taylor et al. 2024; Akins et al. 2024), with the transition occurring at the rest-frame Balmer edge (Setton et al. 2024; Kokorev et al. 2024; Labbe et al. 2024). The presence of broad ($\gtrsim 10^3$ km s^{-1}) Hβ lines and, in some cases, Hβ absorption and a Balmer break stronger than can be readily accommodated with a stellar population (Inayoshi & Maiolino 2025; Ji et al. 2025; Naidu et al. 2025; de Graaff et al. 2025) suggest that the main source of emission is accretion onto a massive black hole (BH). Photoionization models (e.g. Inayoshi et al. 2024; Naidu et al. 2025) show that parameters of $n \sim 10^{11}\,\mathrm{cm}^{-3}$, ionization parameter $U \sim 0.1$, and column density $N_H \sim 10^{26}\,\mathrm{cm}^{-2}$ can produce the strong Balmer lines and break seen in LRDs. The failure to detect X-rays from LRDs has been interpreted as evidence that high column densities associated with super-Eddington accretion can suppress or obscure any coronal emission (Pacucci & Narayan 2024; Madau & Haardt 2024; Lambrides et al. 2024; Inayoshi et al. 2024; Rusakov et al. 2025).

These considerations have naturally led to speculation about the dynamical and energetic connections between the accreting black hole and envelope such as a "black hole star" (BH*: Naidu et al. 2025) and analogous configurations supported by rapid infall from the environment (Rusakov et al. 2025; Kido et al. 2025). Arguing inductively from observational and dynamical constraints, these proposals point out that LRD spectra can be reproduced with envelopes much less massive than the BH. In this paper, however, we take a deductive approach, placing LRDs in the context of a variant of the direct collapse model for supermassive black hole (SMBH) seed formation (e.g., Haehnelt & Rees 1993; Umemura et al. 1993; Loeb & Rasio 1994; Eisenstein & Loeb 1995; Madau & Rees 2001; Bromm & Loeb 2003; Begelman et al. 2006; Lodato & Natarajan 2006; Volonteri et al. 2008; Alexander & Natarajan 2014; Shlosman et al. 2016; Natarajan et al. 2017; Pacucci et al.

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2017; Wise et al. 2019). We argue that LRDs could be "quasi-stars" seen in the latter stages of their evolution. Quasi-stars are hypothetical objects that consist of BHs embedded in and accreting from gaseous envelopes with masses comparable to or greater than the BH mass. They were predicted to be the outcome of SMBH seed formation via core collapse of a supermassive star (SMS: Begelman et al. 2006). Since SMSs require accretion rates of $\gtrsim 0.1 M_\odot$ yr^{-1} to form (Begelman 2010; Hosokawa et al. 2012, 2013) and quasi-stars are predicted to last for tens of Myr, they would naturally acquire masses of millions of solar masses toward the end of their lives. For reasons we will discuss in §2, we define a "late-stage" quasi-star to be one where the BH mass is $\gtrsim 0.1$ of the total mass (BH + envelope).

Quasi-stars are powered by accretion onto the central BH at a rate that liberates the Eddington luminosity for the combined mass of the BH + envelope, which can greatly exceed L_E for the BH alone. As a result, the mass of a BH inside a quasi-star grows linearly with time instead of exponentially (Coughlin & Begelman 2024). Therefore, a quasi-star spends most of its lifetime in the late stage of its evolution and we are most likely to see them in this stage. But do they look like LRDs? In §2 we review the recent theoretical work on late-stage quasi-stars by Coughlin & Begelman (2024), contrasting it with earlier models that suggested the dispersal of the quasi-star envelope at lower BH masses. We also extend this work to sketch the main characteristics of a quasi-star's radiative layer and photosphere. In §3 we show that the resulting spectra may be consistent with observations of LRDs, including the red colors and Balmer break. The broadening of the Balmer lines could be due to strong electron scattering between the thermalization layer and the photosphere, rather than Doppler broadening by bulk motion as a simple analogy with AGN broad-line regions would suggest. We consider the evolutionary status of LRDs-as-quasi-stars in §4, and discuss other potential observational signatures and summarize our argument in §5.

2. LATE-STAGE QUASI-STARS

Early models of quasi-stars treated the case where the BH mass is a small fraction (typically $\lesssim 1\%$) of the total mass, as may be the case shortly after core-collapse of the SMS (Begelman et al. 2008). The innermost region is treated as a modified Bondi accretion flow, through which the energy liberated by accretion percolates convectively. Outside the Bondi radius, the quasi-star envelope is described as a convective ($\gamma = 4/3$) polytrope dominated by radiation pressure. Ball et al. (2011) showed that these models fail when the BH mass $M_{\rm BH}$ exceeds $\sim 1\%$ of the total quasi-star mass M_*, which is roughly the point at which the mass inside the Bondi radius becomes comparable to $M_{\rm BH}$. Citing the Schönberg-Chandrasekhar limit, Ball et al. (2012) argue that the interior structure must become drastically different in order for quasi-stars to exist with higher mass ratios.

Coughlin & Begelman (2024) showed that the problems raised by Ball et al. (2011, 2012) can be addressed if the modified Bondi flow is replaced by an extended region of highly saturated convection, which carries a luminosity

$$L = 4\pi r^2 \beta p c_s, \tag{1}$$

where $c_s = (4p/3\rho)^{1/2}$ is the sound speed associated with the radiation pressure p and $\beta \lesssim 1$ is an efficiency factor. Imposing hydrostatic equilibrium in this inner region implies

$$p \sim \frac{L}{(GM_{\rm BH})^{1/2}} r^{-3/2} \qquad \rho \sim \frac{L}{(GM_{\rm BH})^{3/2}} r^{-1/2}. \tag{2}$$

Detailed numerical models by Coughlin & Begelman (2024) showed that the saturated convection zone transitions smoothly to weak convection at roughly the radius where the enclosed gas mass is comparable to the BH mass. The polytropic convection zone can then be integrated outward until (formally) the density and pressure vanish or, more realistically, the quasi-star develops a radiative layer and photosphere. Coughlin & Begelman (2024) did not consider the structure and properties of the radiative layer but were able to show — under extremely conservative assumptions about the convective flux (i.e., that it continues to carry all the luminosity near the outermost layers, without correcting for the increasing fraction carried by radiative diffusion) — that the BH could grow to at least 61% of the total mass.

A striking feature of these models is the insensitivity of their global properties to the BH mass once $M_{\rm BH}$ exceeds $\sim 0.1 M_*$ (see Coughlin & Begelman 2024, Fig. 6). According to these models, the radius of a late-stage quasi-star is given by

$$R_* \approx 6 \times 10^{16} \beta_{-1}^{2/5} M_6^{3/5} \text{ cm}, \tag{3}$$

where $\beta = 0.1\beta_{-1}$ and $M_* = 10^6 M_6 M_\odot$. Since the quasi-star luminosity must be close to the Eddington limit, $L_E = 1.4 \times 10^{44} M_6$ erg s^{-1}, the effective temperature is

$$T_{\rm eff} \approx 3000 \beta_{-1}^{-1/5} M_6^{-1/20} \text{ K}. \tag{4}$$

The other feature of the models that is robustly fixed throughout the weakly convective region is the constant ratio of gas pressure to radiation pressure, $p_{\rm gas}/p_{\rm rad} \approx 3.3 \times 10^{-3} M_6^{-1/2}$, corresponding to an equation of state

$p \approx 1 \times 10^{19} M_6^{2/3} \rho^{4/3}$ [cgs].[1] These intrinsic quasi-star properties can be used to analyze the radiative, thermal and dynamical properties of the surface layers, where escaping radiation is produced.

Despite their similar temperatures, the surface layers of late-stage quasi-stars differ from the photospheres of lower main sequence stars and red giants in two fundamental ways. First, their low densities imply that electron scattering is the dominant opacity. This means that the outermost layers of late-stage quasi-stars depart from Local Thermal Equilibrium (LTE) and have color temperatures that are substantially higher than their effective temperatures — unlike main sequence stars and red giants but similar to accretion disks in X-ray binaries (Shimura & Takahara 1995; Merloni et al. 2000). Second, the low density means that hydrogen can remain highly ionized down to temperatures as low as ≈ 6000 K, whereas (for example) the much denser solar photosphere is extremely neutral.

Assuming these features (the self-consistency of which can be checked a posteriori), we can estimate the properties of the outermost sub-surface layer, of thickness $\Delta r < R_*$, where LTE is marginally maintained. From hydrostatic equilibrium, we estimate the (radiation) pressure in this layer to be

$$p_{\rm LTE} \approx \frac{GM_*}{\kappa_{\rm sc} R_*^2}\tau_{\rm sc} \approx 0.1 \left(\frac{n}{n_e}\right) \beta_{-1}^{-4/5} M_6^{-1/5} \tau_{\rm sc} \text{ erg cm}^{-3}, \tag{5}$$

where $\tau_{\rm sc} \approx \rho\kappa_{\rm sc}\Delta r$ is the scattering optical depth and we use the electron scattering opacity $\kappa_{\rm sc} = 0.34(n_e/n)$ cm^2 g^{-1}, where n_e/n is the ionization fraction. The condition for maintaining LTE is $\tau_{\rm abs}\tau_{\rm sc} \approx 1$ (Rybicki & Lightman 1979) where $\tau_{\rm abs} = \rho\kappa_{\rm abs}\Delta r$ and $\kappa_{\rm abs}$ is the absorption opacity. The two plausible contributions to $\kappa_{\rm abs}$ are H^- bound-free opacity and free-free absorption of hydrogen. Because the ionization is so high at the LTE layer, the H^- abundance can be estimated using the Saha equation for hydrogen alone and should not be sensitive to the presence or absence of trace metals. We assume a photoionization cross-section of 3×10^{-17} cm^{-2}, appropriate for the temperatures under consideration (Wishart 1979). For free-free absorption we use a Kramers opacity $\kappa_{\rm abs} = A\rho(n_e/n)^2 T^{-7/2}$ [cgs] where $A = 10^{23} A_{23}$ [cgs] and $T = (3p/a)^{1/4}$.

Because of the dependence of $\kappa_{\rm abs}$ and the ionization fraction on the density, the condition for LTE depends on the equation of state near the quasi-star surface. The simplest default is to assume that the relation for the convective interior holds all the way to the marginal LTE layer. We will argue shortly that this assumption may not be correct, but it does allow a baseline analytic model that illustrates the kind of dependences we should expect. We write the equation of state in a slightly generalized form as

$$\rho = 6 \times 10^{-26} \chi M_6^{-1/2} T^3 \text{ g cm}^{-3} \tag{6}$$

where T is in Kelvin and we take $\chi = 1$ for the default model. By changing χ, we will illustrate later how changes in the specific entropy of the outer envelope affect its properties. Since the marginal LTE layer in the default case turns out to be nearly fully ionized, we can make analytic estimates by setting $n_e = n$.

In this limit, there is no solution where the absorption opacity is dominated by H^-. From equation (6) and the LTE condition for free-free absorption, we obtain

$$\tau_{\rm sc} \approx 7.5 A_{23}^{-1/2} M_6^{1/4} T^{1/4}; \tag{7}$$

combining this with equation (5) then gives

$$T_{\rm LTE} \approx 7200 A_{23}^{-2/15} \beta_{-1}^{-16/75} M_6^{1/75} \text{ K}, \tag{8}$$

$$\tau_{\rm sc} \approx 70 A_{23}^{-8/15} \beta_{-1}^{-4/75} M_6^{19/75}, \tag{9}$$

$$\rho_{\rm LTE} \approx 2 \times 10^{-14} A_{23}^{-2/5} \beta_{-1}^{-16/25} M_6^{-23/50} \text{ g cm}^{-3}, \tag{10}$$

and

$$\Delta r \approx 10^{16} A_{23}^{-2/15} \beta_{-1}^{44/75} M_6^{107/150} \text{ cm}, \tag{11}$$

implying $\Delta r/R_* \approx 0.2 A_{23}^{-2/15} \beta_{-1}^{14/75} M_6^{17/150}$. A numerical solution assuming fiducial parameters $M_6 = \beta_{-1} = 1$ and calculating n_e/n self-consistently gives nearly identical results, which is not surprising since the ionization fraction is 0.96.

A detailed analysis of convection near R_* is beyond the scope of this paper, but simple arguments suggest that convection must become inefficient at some depth $(\Delta r)_r$ below the surface, where $(\Delta r)_r \sim (R_*^3/GM_*)^{1/2}(p/\rho)_r^{1/2}$ is also roughly the scale height at that depth. Convective instability fails when the radiative diffusion timescale across $(\Delta r)_r$, $t_{\rm diff} \sim \rho\kappa_{\rm sc}(\Delta r)_r^2/c$, becomes shorter than the buoyancy timescale, $t_{\rm buoy} \sim (R_*^3/GM_*)^{1/2}(\Delta r/R_*)_r^{1/2}$. Outside $(\Delta r)_r$, we would

[1] This equation of state corresponds to $p/\rho^{4/3} \equiv K \approx 1GM_*^{2/3}$, which can be compared to the unique value for an $n = 3$ polytrope, $K = 0.364GM_*^{2/3}$. The difference presumably arises from the different inner boundary conditions applied in the two cases.

naively expect all of the luminosity to be carried by radiative diffusion.[2]

Using our fiducial parameters, the fraction of quasi-star mass outside $(\Delta r)_r$ can be estimated to be $(\Delta M)_r/M_* \sim 0.04$. But this number turns out to be too large for comfort. Throughout the convective zone, the diffusive luminosity varies with radius as $L_{\rm rad}(r) = L_{E*}[M(r)/M_*](1-p_g/p_r)$, where L_{E*} is the Eddington limit for the entire mass M_* (assuming constant opacity, which is reasonable for this argument), $M(r)$ is the enclosed mass at r, and p_g/p_r is the fixed ratio of gas-to-radiation pressure. Convection carries the difference between $L_{\rm rad}(r)$ and the total luminosity L, which is independent of r. Now, at $(\Delta r)_r$, we have argued that $L_{\rm rad}$ becomes fixed and equal to L. But what is the value of L? If it is equal to the local Eddington limit at $R_* - (\Delta r)_r$, then this is about 4% lower than L_{E*} because 4% of the mass is located outside $(\Delta r)_r$. So the radiation pressure would fall 4% short of the value needed to support the outermost layers of stellar mass. Gas pressure would have to take up the slack, but we have seen that $p_g/p_r \sim 0.003$ in the convective interior, i.e., it is about 10 times too weak to provide the necessary support.

Therefore, L cannot be as small as the local Eddington limit at $(\Delta r)_r$; it must be close to L_{E*}. In this case, the radiative flux would exceed the Eddington limit near $(\Delta r)_r$. In perfect spherical symmetry, the outward radiation pressure gradient would have to be balanced by a steep *inward* gradient of gas pressure, creating a density inversion. In practice, this is probably highly unstable, leading to vigorous mixing where gas is lifted into the radiative layer by the radiation force, leading to a decrease in the specific entropy. The result should be a steep increase of p_g/p_r, possibly to a level of order $(\Delta M)_r/M_*$. This would correspond to $\chi \sim 10$ in equation (6).

It is straightforward to recalculate the LTE conditions for larger values of χ. For $\chi = 10$, H^- dominates the absorption and the temperature at which LTE is marginal (i.e., the color temperature of the quasi-star) drops to ≈ 6500 K, with a much lower scattering optical depth of ≈ 17 and an ionized fraction of 0.37. Even the extreme case $\chi = 100$ would give a similar temperature, $T_{\rm LTE} \approx 6400$.

We can now check the assumptions that went into these estimates. According to the analytic results for the default case $\chi = 1$, the results are insensitive to M_* and the parameters A and β. At densities as low as $\rho_{\rm LTE}$ ($n_{\rm LTE} \sim 10^{10}$ cm^{-3}), the opacity due to H^- is unimportant for thermalizing the radiation but becomes dominant for higher ratios of gas pressure to radiation pressure (larger χ). For all cases considered, the Saha equation predicts a non-negligible ionization fraction, ranging from 0.1 (for the extreme case $\chi = 100$) to $\gtrsim 0.9$. Finally, our estimated value of $\Delta r/R_*$ is sufficiently small to validate our assumption of a thin layer, while cautioning us not to take the exact numbers too seriously.

To summarize, the Coughlin & Begelman (2024) model of late-stage quasi-stars predicts a scattering-dominated photosphere with a color temperature of $\sim 6000-7000$ K and an effective temperature ~ 3000 K, insensitive to both M_* and $M_{\rm BH}$. The scattering optical depth (assuming the $\chi \sim 10$ model as most plausible) is $\tau_{\rm sc} \sim 10-20$. As in luminous accretion disks, the color correction factor is given by $\sim \tau_{\rm sc}^{1/4}$ in the limit $\tau_{\rm sc}^{1/4} \gg 1$.

3. QUASI-STAR SPECTRA

The combination of relatively low temperatures with high scattering optical depths of late-stage quasi-star atmospheres provides conditions conducive to reproducing several observed features of LRDs:

- Red colors. Late-stage quasi-stars should have spectra similar to $\approx 6000-7000$ K blackbodies. Using stacked data from Akins et al. (2024), Kido et al. (2025) has shown that such spectra (with modest extinction) provide a reasonable fit, although a slightly cooler blackbody would work even better. We note that our color temperature estimates are extremely crude and that temperatures as low as 6000 K could be accommodated with relatively high ionization levels, given the low densities.

- Strong Balmer break. The Boltzmann equation for hydrogen in the marginal LTE zone gives a ratio of $n = 2$ to ground state population of $n_2/n_1 = 4\exp(-1.18\times10^5/T) = 2\times10^{-7}$ for $T = 7000$ K. Assuming a neutral fraction x, number density $10^{10}n_{10}$ cm^{-3} and layer thickness $10^{16}\Delta r_{16}$ cm, the $n = 2$ column density in the marginal LTE zone is $N_2 = 2\times10^{19} x n_{10}\Delta r_{16}$ cm^{-3}. Since the absorption cross-section at the Balmer edge is

[2] This is a weaker condition than the one used by Begelman et al. (2008) and Coughlin & Begelman (2024), who argued that convection would shut off when the saturated limit dropped below the total luminosity L. This is probably not a valid criterion in the outer layers because, by this point, most of the quasi-star mass is enclosed and most of L is accounted for by radiative diffusion near the local Eddington limit. Convection only needs to carry only a small fraction of L near the outer boundary of the convective zone.

$\sim 10^{-17}$ cm^2, this is ample to produce a strong Balmer break if the gas is less $\lesssim 99\%$ ionized, or if the column density is higher — both consistent with our models.

- Balmer emission lines. The likelihood of forming a strong Balmer break goes hand-in-hand with the formation of Balmer emission lines in the non-LTE scattering layer. The large $n = 2$ population means that Balmer lines are likely to remain optically thick well above the layer where continuum radiation goes out of equilibrium. As the intensity of the continuum is diluted by scattering, the line intensity can be maintained at closer to its Planck value for the temperature, and thus stand out in emission. A more extreme limit of this process is thought to produce Balmer (and other) lines in the outer regions of cataclysmic variable accretion disks, which can be optically thin to continuum while being optically thick in the lines (Williams 1980; Williams & Shipman 1988).

- Scatter-broadened lines. The Keplerian speed at R_* is given by $v_* \approx 500\beta_{-1}^{1/5} M_6^{1/5}$ km s^{-1}, too small to account for the observed linewidths of $2000 - 3000$ km s^{-1}. The electron thermal speeds in the scattering layer are $v_e \sim 300$ km s^{-1}, opening up the possibility that the line widths are established by repeated scattering. Since the broadened linewidth is $\sim \tau_{\rm sc} v_e/c$, the optical depths estimated in our default $\chi = 1$ model ($\tau_{\rm sc} \sim 70$) would over-broaden the lines and perhaps smear them out entirely, if the line emission passed through the entire scattering layer. Rusakov et al. (2025) found good fits to the exponential profile predicted for scatter-broadening in a sample of observed LRDs if $\tau_{\rm sc} \sim O(1)$, still much smaller than our best-guess estimates of $\tau_{\rm sc} \sim 10 - 20$ for the $\chi = 10$ model. Since most of the line emission might arise high in the atmosphere where the mismatch between color temperature and brightness temperature in the continuum is greatest, the scattering depth sampled by the emission lines might be limited to a small fraction of the total, thus limiting the amount of broadening. We note that the Balmer breaks observed in LRDs tend to be smeared over an extremely broad range of wavelengths, which could indicate that they are formed much closer to the LTE layer and thus undergo a larger amount of scatter-broadening than the lines.

- No X-rays. The large electron column densities in the scattering layer would eliminate any X-rays produced behind it.

Our intent in this section is to sketch (mainly) qualitatively a few predicted aspects of the late-stage quasi-star spectra that can be compared to LRD observations. These need to be fleshed out with more detailed modeling.

4. EVOLUTIONARY CONTEXT OF QUASI-STARS/LRDS

The time required for a BH to reach a mass fraction $\epsilon = M_{\rm BH}/M_*$ inside a quasi-star is

$$t(\epsilon) \approx \epsilon\eta_{-1}(39 - 77) \text{ Myr}, \tag{12}$$

where $\eta = 0.1\eta_{-1}$ is the BH accretion efficiency and the lower value of the range corresponds to fixed M_* while the higher value applies whenever the quasi-star envelope gains significant mass by accretion during this period (Coughlin & Begelman 2024). Coughlin & Begelman (2024) argued that ϵ could not exceed 0.62 but this was based on an overly restrictive assumption about the luminosity that had to be carried by convection (i.e., it ignored the large and increasing fraction of L carried radiatively near the outer layers); therefore, we can't exclude the possibility that ϵ could be larger and might approach 1. The linear growth rate implies that the number of quasi-stars seen at different evolutionary stages is roughly proportional to ϵ, with late-stage quasi-stars being most common.

According to the proposed formation scenario (Begelman et al. 2006; Begelman 2010), quasi-stars are set up following core collapse of an SMS (Fig. 1). The "prompt" black hole mass following core collapse might only be a tiny fraction of the total SMS mass, depending on the internal angular momentum distribution of the star. The energy liberated during the initial collapse is insufficient to unbind the SMS envelope, which instead expands and settles into a convective configuration (Begelman et al. 2008) with the internal accretion rate onto the black hole adjusting so that it liberates the Eddington limit corresponding to the mass of the entire envelope, not just that of the central black hole.

A mass supply rate of $\dot{M} \gtrsim 0.1 M_\odot$ yr^{-1} from the local environment is a necessary condition to create an SMS, which increases in mass on a timescale shorter than its Kelvin-Helmholtz time until hydrogen ignites in its core (Begelman et al. 2006; Hosokawa et al. 2012, 2013). Although ignition occurs at a relatively modest stellar mass $\sim 10^3 M_\odot$ (Begelman et al. 2006; Begelman 2010), by the time core collapse occurs after ~ 2 Myr the total mass has increased to $\sim 2\times 10^5 \dot{M}_{-1} M_\odot$, where $\dot{M} = 0.1\dot{M}_{-1}$ $M_\odot$ yr^{-1}. If the initial mass supply rate is steady for tens of Myr then most quasi-stars and their central BHs should reach masses of at least several million $M_\odot$ by their late stages. The final masses could

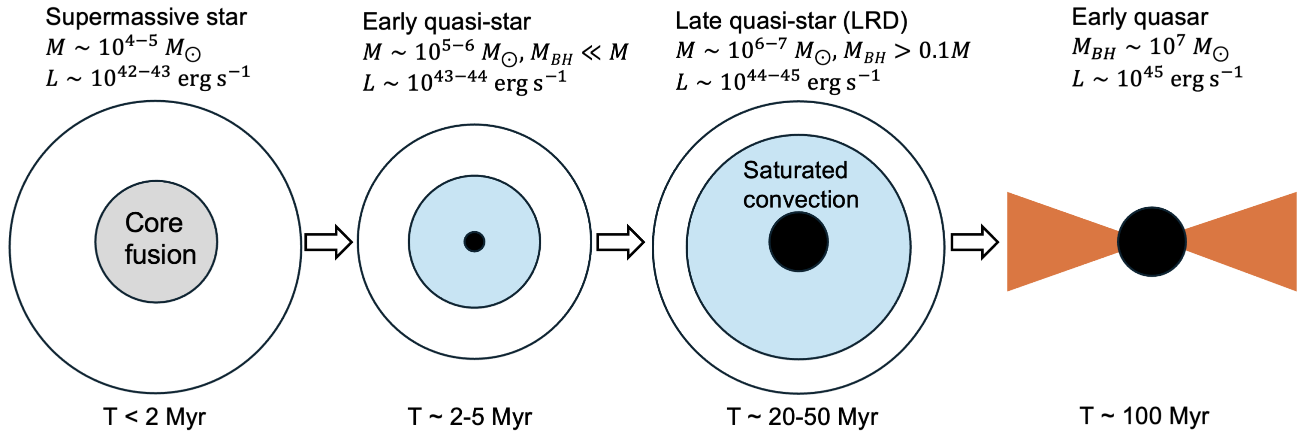

Figure 1. Schematic diagram showing proposed stages in the formation and early growth of supermassive black holes from left to right. Approximate total (M) and black hole (M_{BH}) masses, luminosities L, and lifetimes T are very rough estimates assuming a continued infall rate of $\gtrsim 0.1 M_\odot$ yr^{-1}. We propose that observed little red dots correspond to late quasi-stars. Rare precursors should appear bluer in color at similar or lower luminosity.

be lower if the mass supply is intermittent on shorter timescales or if there is a high rate of mass loss. On the other hand, there could be systems with inflow rates substantially larger than the minimum required, leading to quasi-star and BH masses $\gtrsim 10^7 M_\odot$. For our discussion below, we will assume that the $\dot{M}$ distribution is skewed to smaller values and that the typical late-stage quasi-star has a mass of a few times $10^6 M_\odot$ up to $\sim 10^7 M_\odot$ and a bolometric luminosity of $\sim 10^{44} - 10^{45}$ erg s^{-1}.

LRDs have a comoving density of $\sim 10^{-5}$ cMpc^{-3} at $z \sim 5-6$, making them ~ 100 times less common on the sky than UV-selected galaxies (Greene et al. 2024). However, if we have correctly estimated the typical age of a quasi-star as $\sim 2-4\%$ of the age of the universe at $z \sim 5$, they must be remarkably common as a physical phenomenon: at some point, a significant fraction of high-redshift galaxies must host an LRD. This suggests that LRDs — and by inference, SMSs and quasi-stars — are ubiquitous features of SMBH formation and possibly the main channel.

Assuming that only 1 in 25 LRDs is active at any given time at $z \sim 5$, the BH mass density associated with LRDs/quasi-stars is $\sim 250 M_6 M_\odot$ cMpc^{-3}. If a typical LRD black hole subsequently grows (as an AGN) by a factor of $\sim 100 M_6^{-1}$ following its quasi-star epoch to become an SMBH with a median mass $\sim 10^8 M_\odot$, then the BH mass density resulting from LRD/quasi-star seeds is $\sim 2.5 \times 10^4 M_6 M_\odot$ cMpc^{-3}, only a few times smaller than the present-day BH mass density (Yu & Tremaine 2002). Several factors, including shorter lifetimes, could increase the contribution of LRDs to the present-day BH population. A ubiquitous quasi-star/LRD stage, in which SMBHs acquire their first $\sim 10^6 - 10^7 M_\odot$ of mass in only a few 10's of Myr, could have important implications for galaxy formation. Because this growth is first smothered within the quasi-star, feedback is relatively ineffective and only affects star formation as the BH grows further, as an AGN, within a more massive merged host galaxy.

5. DISCUSSION

Our proposed identification of LRDs with late-stage quasi-stars is based on two arguments: 1) the similarity of predicted quasi-star atmospheres with the radiating layers inferred to exist in LRDs from their observational properties (e.g. Inayoshi & Maiolino 2025; Ji et al. 2025; Naidu et al. 2025; de Graaff et al. 2025; Kido et al. 2025); and 2) the fact that quasi-stars are a natural prediction of SMBH seed formation through the core collapse of SMSs. LRD radiative models already in the literature posit relatively low-mass envelopes associated with an accretion flow or supported in some other way (or assumed by fiat), but the mass estimates obtained are similar to the masses of the *observable* part of our massive quasistar envelopes. For example, the layer producing the thermalized emission in our default model (§2) has a mass

$$\Delta M \approx 4 \times 10^3 A_{23}^{-8/15} \beta_{-1}^{56/75} M_6^{109/75}\ M_\odot, \tag{13}$$

or $\Delta M / M_* \approx 4 \times 10^{-3}$. But the extant models differ from the quasi-star model conceptually in that the radiating layer in the quasi-star model forms a thin veneer overlying an extremely massive envelope that determines the radiating layer's properties. Rather than thinking of this layer as a kind of AGN broad line region photoionized by a central source, we argue that it is more appropriate to think of it as a convectively powered envelope producing its own radiation in situ (as in the model by Kido et al. 2025) — like a true star.

In detail, we find other important differences between the quasi-star picture and other models. The quasi-star radius is significantly larger than radii assumed in other models, by up to an order of magnitude. The radial scale is set by convective processes in the deep interior and cannot be chosen arbitrarily, although refinements of the convective modeling — which may change the radius somewhat — are certainly warranted. Another key feature we have emphasized — partly the result of the large radius — is that our radiating layers are highly ionized and dominated by electron scattering, despite their relatively low temperatures. This means that the color temperatures of quasi-star/LRDs can be a factor $\gtrsim 2$ times larger than their effective temperatures.

From an evolutionary perspective, the most important implication of our model is that LRDs should be short-lived — the central BH can swallow the entire envelope (or as much of it as is allowed) in roughly one Salpeter time, modulo an uncertain numerical factor. This is true regardless of the initial BH mass, because the accretion rate is tied to the Eddington limit for the entire envelope. Unless the external mass supply rate $\dot{M}$ exponentiates with time to keep pace — which seems unlikely — the Eddington limit of the black hole will outrun the mass supply and the LRD/quasi-star phase will end. Thus, the small observed number of LRDs compared to UV-selected galaxies does not mean that LRDs are physically rare, but quite the opposite: essentially every galaxy must host an LRD at some point. We therefore propose that LRDs are an integral stage of the formation and growth process of supermassive black holes.

As we have noted, low-mass gaseous envelopes that reproduce the observed properties of LRDs could be difficult to distinguish from the atmospheres of quasi-stars — some mechanisms for producing them have been discussed in the literature (e.g. Begelman 2012; Kido et al. 2025). Such stand-alone envelopes could thus provide an alternative to the model discussed here. However, the large inferred population of quasi-star/LRDs puts pressure on how important these processes could be for producing additional LRD episodes after the end of the quasi-star stage.

The picture of LRDs as quasi-stars carries with it an evolutionary sequence that includes stages prior to and following the phenomena we have focused on in this paper. We have illustrated this sequence schematically in Fig. 1. The SMS stage should last only $\sim 2-5\%$ of a late-stage quasi-star lifetime and should thus be rarest on the sky. They should also be $\sim 10-100$ times less luminous on average, i.e. $L \sim 10^{42}-10^{43}$ erg s^{-1}, with color temperatures ranging from ~ 5000 K at lower masses to $\sim 10^4$ K as masses approach $10^5 M_\odot$ (Hosokawa et al. 2013). Early-stage quasi-stars should be more common than SMSs ($\sim 10\%$ compared to late-stage quasi-stars) and — at constant envelope mass — should evolve from hotter (several $\times 10^4$ K) to cooler color temperatures as the BH grows inside (Coughlin & Begelman 2024). However, this evolution could be obscured by the diversity of quasi-star masses and mass ratios. Efforts should be made to find the immediate precursors to LRDs. Little is known about the fate of a quasi-star once the BH swallows most or all of the envelope, e.g., whether the residual gas disperses or is able to settle into a steady state with a much lower envelope mass if matter continues to be supplied from the environment at a sufficient rate (e.g., resembling one of the stand-alone models as in Naidu et al. 2025; de Graaff et al. 2025; Kido et al. 2025). Alternatively, if stripped of their envelopes these immediate post-quasi-stars could be the first proper AGNs in the universe — examples of which may have already been discovered (e.g. Bogdán et al. 2024; Natarajan et al. 2024).

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