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Little Red Dots are Tidal Disruption Events in Runaway-Collapsing Clusters

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ABSTRACT

I hypothesize a physical explanation for the "Little Red Dots" (LRDs) discovered by the James Webb Space Telescope (JWST). The first star formation in the universe occurs in dense clusters, some of which may undergo runaway collapse and form an intermediate mass black hole. This process would appear as a very dense stellar system, with recurring tidal disruption events (TDEs) as stellar material is accreted by the black hole. Such a system would be compact, UV-emitting, and exhibit broad Hα emission. If runaway collapse is the primary mechanism for forming massive black hole seeds, this process could be fairly common and explain the large volume densities of LRDs. In order to match the predicted number density of runaway collapse clusters, the tidal disruption rate must be on the order of 10^{-4} per year. A top-heavy stellar initial mass function may be required to match observations without exceeding the predicted ΛCDM mass function. The TDE LRD hypothesis can be verified with followup JWST observations looking for TDE-like variability.

Keywords: High-redshift galaxies(734) — Intermediate-mass black holes(816) — Galaxy formation(595) — Tidal disruption(1696) — Active galactic nuclei(16)

1. INTRODUCTION

The objects known as Little Red Dots (LRDs) discovered by the James Webb Space Telescope (JWST) have been mystifying our community (Greene et al. 2024; Kocevski et al. 2024; Kokorev et al. 2024; Matthee et al. 2024). They exhibit features common to both star-forming galaxies and active galactic nuclei (AGNs), but their emission cannot be modeled robustly by either (or a combination). Their number density at high redshift is also higher than expected compared to similar galaxy populations. If they are dominated by star formation, they are more compact than anything ever seen before (Guia et al. 2024a), and exceed the predicted stellar mass function allowed by ΛCDM (Boylan-Kolchin 2023; Baggen et al. 2024a; Akins et al. 2024). If they are dominated by AGN emission, their existence implies an almost 100% AGN fraction in high-redshift galaxies (Greene et al. 2024). Both of these possibilities are difficult to reconcile with any cosmic evolution model.

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LRDs have been discovered mostly at redshifts $5 < z < 8$, and often exhibit a "V-shaped" spectral energy distribution (SED). The bottom of the "V" is at the Balmer break (Setton et al. 2024), with rising luminosity both in the UV and red wavelengths. They have broad Hα emission lines but the broadness is not seen in Hβ (Brooks et al. 2024; Maiolino et al. 2024). They are X-ray undetected or weak (Yue et al. 2024) and are also undetected in the far-infrared (Labbe et al. 2023; Pérez-González et al. 2024; Williams et al. 2024). This lack of emission not only makes the SEDs very difficult to characterize and bolometric luminosities hard to determine, but there is an overall struggle to pinpoint the source of the emission at all.

One of the many reasons LRDs are fascinating is their potential to shed light on the formation and evolution of supermassive black holes (SMBHs). The formation mechanism of SMBH seeds, often thought to be intermediate mass black holes (IMBHs) of some variety, is highly unconstrained, as is their subsequent growth into SMBHs. Seeds may be "light" (i.e. the remnants of the first stars, e.g. Bromm & Loeb (2003)), "heavy" (i.e. direct collapse black holes, e.g. Begelman et al. (2006)), or in-between (i.e. remnants of runaway cluster collapse, e.g. Devecchi & Volonteri (2009)), and are likely to undergo at least some phases of super-Eddington growth to reach supermassive size. Observations of the earliest galaxies could untangle this quandary - or at least we thought so.

In this Letter I explore the hypothesis that Little Red Dots can be explained by black hole seeds in-the-making via tidal disruptions in runaway collapsing clusters. The resulting SED would somewhat resemble an AGN but with some key differences, many of which are consistent with LRD observations.

2. RUNAWAY COLLAPSE

One prominent theory for the formation of black hole seeds is the runaway collapse of dense star clusters. It is thought to create seeds of $\sim 1000 M_{\odot}$ and may or may not be redshift dependent, depending on whether metallicity is an important factor. The phenomenon of runaway collapse involves a dynamical instability resulting in the collapse of the cluster core. This process may result in a supermassive star, which then evolves into an intermediate mass black hole (Devecchi & Volonteri 2009), or may involve a pre-existing black hole which rapidly accretes surrounding objects in the cluster (Guia et al. 2024b; Baggen et al. 2024b; Devecchi & Volonteri 2009; Davies et al. 2011). Regardless of the precise order of operations, a dense cluster surrounding a massive black hole will be an efficient environment for tidal disruption events. In fact, Alexander & Bar-Or (2017) suggest that intermediate mass black holes should not exist at all because growth from TDEs is so efficient that the minimum MBH mass is $10^5 M_{\odot}$.

There have been very few calculations of the number density of such seeds with cosmic time, likely because the conditions for runaway collapse happen on a much smaller scale than that of e.g. cosmological simulations. Estimates have been made by Devecchi et al. (2012) (analytic) and Habouzit et al. (2017) (numerical) which I show in Figure 1. The grey shaded area represents an adaptation of the prediction from Devecchi et al. (2012) for a range of seed masses ($300 - 3000 M_{\odot}$). The solid lines are from a cosmological hydrodynamic simulation with a using a subgrid model for cluster-based IMBH formation (Habouzit et al. 2017). The blue line shows a model with delayed cooling after supernova explosions, while the orange represents regular kinetic or thermal supernova feedback.

Also included in this figure are observational results of LRDs from JWST: Greene et al. (2024) (green dots), Kocevski et al. (2024) (red stars) and Kokorev et al. (2024) (black diamonds). The observed points are about 4 orders of magnitude below the predicted density of black hole seeds formed through cluster collapse. A canonical TDE has a peak bolometric luminosity of $\sim 10^{44}$ erg s^{-1} and remains observable for about 1 year (Gezari 2021). Therefore, a TDE rate of 10^{-4} per year could explain the fraction of observed LRDs vs the occupation of black holes in galaxies.

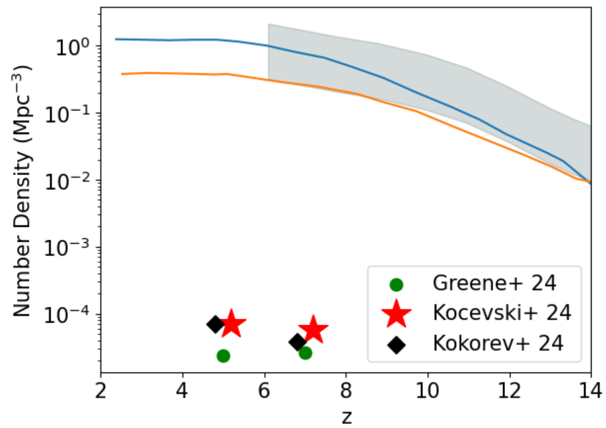

Figure 1. Comoving number density of runaway collapse black hole seeds vs redshift. Predictions from numerical simulations vary based on whether a delayed cooling model is used with supernova feedback (blue line) or not (orange line) (Habouzit et al. 2017). Analytic predictions using variable seed masses are shown in the grey shaded area (Devecchi et al. 2012). Data points represent JWST LRD observations from Greene et al. (2024) (green dots), Kocevski et al. (2024) (red stars) and Kokorev et al. (2024) (black diamonds). The data are ~ 4 orders of magnitude below the predicted densities.

3. TDE RATES IN LRDS

Tidal disruption events happen when stars enter the tidal radius of a black hole. As a result, approximately half of the star's mass becomes unbound, and the remainder is stretched into streams before being eventually devoured by the black hole. These events likely result in super-Eddington accretion, and are UV bright but often X-ray weak. Broad Hα lines with widths of $3 - 13 \times 10^4$ km s^{-1} are common (Gezari 2021). Their brightness decays with a characteristic $t^{-5/3}$ powerlaw and lasts on the order of 100's of days. I now quantify whether the TDE rate estimated in the previous section is physically reasonable for powering black hole growth.

Stone et al. (2017) suggests that a combination of tidal capture and TDEs can grow a black hole quickly and efficiently. They give the following rate:

$$\dot{N} = n_{\star} \Sigma v_{rel} \tag{1}$$

where the number density of stars $n_{\star} = \rho / M_{\star}$ with a mean stellar mass of M_{*}, v_{rel} is the relative velocity between the MBH and the star (which I take to equal the velocity dispersion σ), and Σ is the tidal-capture cross section, given by

$$\Sigma = \pi R_t^2 \left(1 + \frac{2GM_{tot}}{R_t v_{rel}^2}\right). \quad (2)$$

Here M_{tot} is the total mass ($M_{BH} + M_*$), and R_t is the tidal radius given by $R_t = r_\star \left(M_{BH}/M_\star\right)^{1/3}$ and $r_\star$ is the solar radius multiplied by $M_*^{0.8}$.

In addition to the prior analytic estimate, I consider a rate developed using numerical simulations. Rizzuto et al. (2023) use the BIFROST code (Rantala et al. 2023) to study the growth of a black hole in a cluster direct N-body methods including Post-Newtonian dynamics and a detailed TDE prescription. They devise the following formula which matches their results:

$$\dot{N} = 1.1 F f_b \ln\left(0.22\frac{M_{BH}}{M_*}\right)\left(\frac{M_{BH}}{10^3 M_\odot}\right)\left(\frac{\rho}{10^7 M_\odot \mathrm{pc}^{-3}}\right) \times \left(\frac{100 \mathrm{kms}^{-1}}{\sigma}\right)^3 \mathrm{Myr}^{-1}$$

where F is a numerical prefactor set to 0.8 and f_b is the fraction of bound stars, which is assumed to be 0.2. Using these two rate estimates, I compute expected TDE rates in LRD environments. The stellar densities in LRDs are estimated to be in the realm of $10^6 - 10^8 M_\odot$ pc^{-3}, and I use 10^8 as a fiducial value (Guia et al. 2024a). Using a canonical velocity dispersion for cluster collapse estimated at 40 km s^{-1} (Miller & Davies 2012) and a mean stellar mass of 1 M$_\odot$, I plot the TDE rate in Figure 2 as a function of black hole mass (top) and stellar velocity dispersion (bottom). In the top plot the velocity dispersion is fixed at 40 km s^{-1}, while the bottom plot has a fixed $\mathrm{M_{BH}} = 10^4$ M$_\odot$. The rate estimate by Stone et al. (2017) is plotted in blue and Rizzuto et al. (2023) in red. A rate of 10^{-4} per year is very reasonable within the range of $10^3 M_\odot < M_{\mathrm{BH}} < 10^5 M_\odot$ and/or velocity dispersions of 100 - 150 km s^{-1}. There are no direct constraints on stellar velocity dispersions in LRDs, but it is plausible that with such high densities the values would be large.

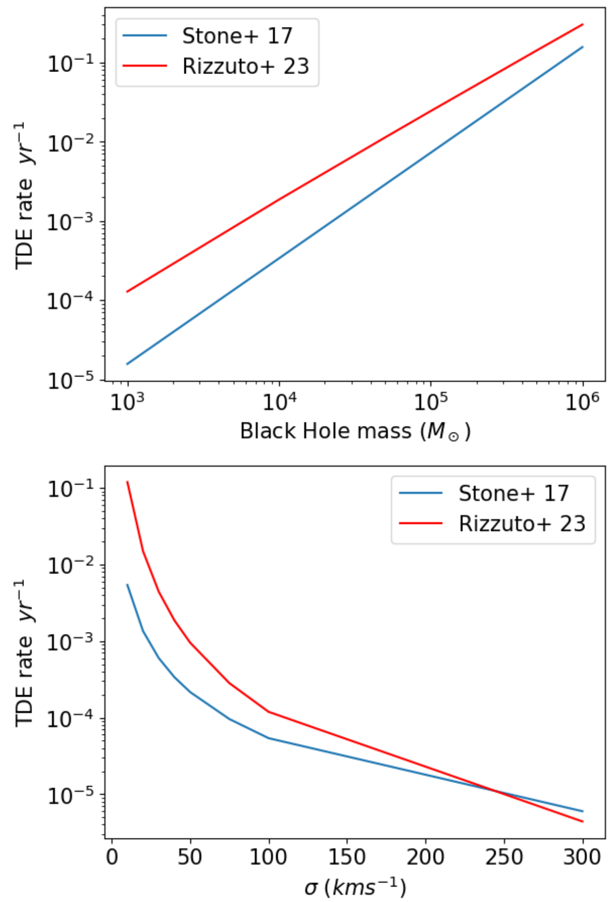

Figure 2. Rates of TDEs for models by Stone et al. (2017) (blue) and Rizzuto et al. (2023) (red). *Top:* TDE rate vs black hole mass, with fixed velocity dispersion of $\sigma = 40$ km s^{-1}. *Bottom:* TDE rate vs stellar velocity dispersion, with fixed black hole mass of 10^4 M$_\odot$.

4. CONCLUSIONS AND CAVEATS

The plethora of LRDs discovered by JWST has challenged models of black hole and galaxy evolution. In this paper I suggest that a primary origin for the emission from LRDs is due to tidal disruption events occurring during the process of forming the seeds of supermassive black holes. The predicted number density of dense stellar clusters undergoing a runaway collapse is about 10^4 times higher than that of LRDs, implying a TDE rate of 10^{-4} per year. Other common attributes include a spectral rise in the UV/optical, broad Hα, and X-ray weakness. The broad Hα emission from TDEs is not correlated with black hole mass (unlike in AGN), providing an explanation for the proposed overmassive nature of these high redshift black holes relative to their host. The Hα lines also show absorption features (Matthee et al. 2024), which could be due to tidal streams of disrupted stars. X-ray weakness is thought to be a sign of super-Eddington accretion, likely combined with a viewing angle effect, and is thought to occur in TDEs. In addition, when TDEs do show X-rays they are soft, which may be redshifted out of the Chandra detection range.

This model fails to directly address the red colors of LRDs. The red part of the SED is likely at least somewhat dominated by stellar light, as evidenced by a common feature of a Balmer break (Setton et al. 2024) (although see Inayoshi & Maiolino (2024)). LRDs do not characteristically show evidence of warm or hot dust (though see Barro et al. (2024)), and therefore a standard AGN model (consisting of a torus) cannot apply. Another common thorn in the side of LRD scientists is the number densities of these objects. If LRDs are assumed to be dominated by AGN, their number densities are not far from those of all galaxies in the universe, implying a near 100% AGN occupation fraction at $z \sim 7$ for the brightest galaxies ($L_{\rm bol} > 10^{45}$ erg s^{-1}). Conversely, if most or all of the light is dominated by star formation, LRDs on their own reach or exceed the predicted stellar mass functions for all galaxies at high redshift in ΛCDM (Boylan-Kolchin 2023; Akins et al. 2024).

These issues can be avoided if one assumes a non-standard initial mass function (IMF). A top-heavy IMF would result in higher luminosity stars, and an overall decrease in stellar mass estimates. I propose that the source of the light is stellar, originating in the dense nuclear cluster surrounding the IMBH, and with a top-heavy IMF. The whole issue of too bright / too many stars is solved if there are actually fewer stars of higher masses. A top-heavy IMF from a metal-poor population could produce the red stellar light, explain a lack of dust (if the environment is very metal-poor), and solve the number density problem. More massive stars would also result in more luminous TDEs. SED models of LRDs with varying IMFs are needed to confirm this suggestion.

LRDs are not all identical, and there is no need for one overarching theory to explain their existence. For example, some objects show strong AGN signatures (Labbe et al. 2024; Wang et al. 2024, see) which likely dominate the SEDs. Therefore, TDEs occurring in runaway collapsing clusters may explain a subset of LRDs, and canonical AGN and other phenomena the others. One way to verify the TDE hypothesis is to search for strong variability in the rest-frame UV (caused by TDE emission) but less in the rest-frame optical/NIR (dominated by stellar light). TDEs have well-known decays in their light curves which can be confirmed fairly straightforwardly. The caveat is that due to time dilation timescales are lengthened by a factor of $(1 + z)$, so decays will occur approximately 6-8 times more slowly than seen in the local universe. Initial searches for variability of LRDs have found none as of yet (Kokubo & Harikane 2024; Tee et al. 2024), highlighting that these objects may have a diverse taxonomy. Follow-up with JWST at appropriate timescales is crucial for verifying the TDE hypothesis.

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