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The Host Galaxy of a Dormant, Overmassive Black Hole at $z = 6.7$ May Be Restarting Star Formation

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ABSTRACT

JWST is discovering a large population of $z > 4$ supermassive black holes (SMBHs) that are overmassive with respect to the stellar content of their hosts. A previous study developed a physical model to interpret this overmassive population as the result of quasar feedback acting on a compact host galaxy. In this Note, we apply this model to JADES GN 1146115, a dormant supermassive black hole at $z = 6.7$ whose mass is $\sim 40\%$ of the host's mass in stars and accreting at $\sim 2\%$ of the Eddington limit. The host has been forming stars at the low rate of $\sim 1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ for the past ~ 100 Myr. Our model suggests that this galactic system is on the verge of a resurgence of global star formation activity. This transition comes after a period of domination by the effect of its overmassive black hole, whose duration is comparable to typical quasar lifetimes.

Keywords: Active galaxies (17) — Galaxy evolution (594) — Star formation (1569) — Supermassive black holes (1663) — Galaxy quenching (2040)

1. INTRODUCTION

The James Webb Space Telescope (JWST) has detected a large population of supermassive black holes (SMBHs) at $z > 4$ with typical masses in the range $10^6 - 10^8\,\mathrm{M}_\odot$ (see, e.g., Harikane et al. 2023; Maiolino et al. 2023). Remarkably, the ratio between black hole mass $M_\bullet$ and stellar mass $M_\star$ is significantly higher than the local value of $\sim 10^{-3}$ (Reines & Volonteri 2015). With a detailed statistical analysis, Pacucci et al. (2023) concluded that the population of galaxies currently probed by JWST host SMBHs that are $10 - 100$ times overmassive with respect to their stellar content, in comparison with the local population of galaxies, and derived a high-z $M_\bullet - M_\star$ relation. Notably, a virtually indistinguishable relation was found, independently, by Inayoshi & Ichikawa (2024).

Significant uncertainties characterize the determination of $M_\bullet$ and $M_\star$, which rely on methods calibrated at low redshift. Pacucci et al. (2023) pointed out that the tension with the local $M_\bullet - M_\star$ relation will vanish if there is a systematic error of a factor $\sim 60 - 70$ in the measurements of the *ratio* between black hole mass and stellar mass, in a way such that the black hole (stellar) masses are overestimated (underestimated). As these galaxies are physically small (i.e., they have effective radii of $r_e \sim 150$ pc, see Baggen et al. 2023), it is unlikely that their stellar masses are underestimated by significant factors.

Pacucci & Loeb (2024) developed a framework to explain this population of overmassive SMBHs at $z > 4$, based on two assumptions. First, these galaxies are small, so the central SMBH has an outsized thermal effect on the entire host. Second, for $z > 4$, the SMBH's growth times are comparable to the age of the Universe; hence, they are constantly injecting energy into the system and heating the gas. Once the central SMBH's duty cycle drops significantly below unity, the gas can finally cool down, and effective global star formation can resume. In this framework, Pacucci & Loeb (2024) derived a condition for the average star formation efficiency to be quenched.

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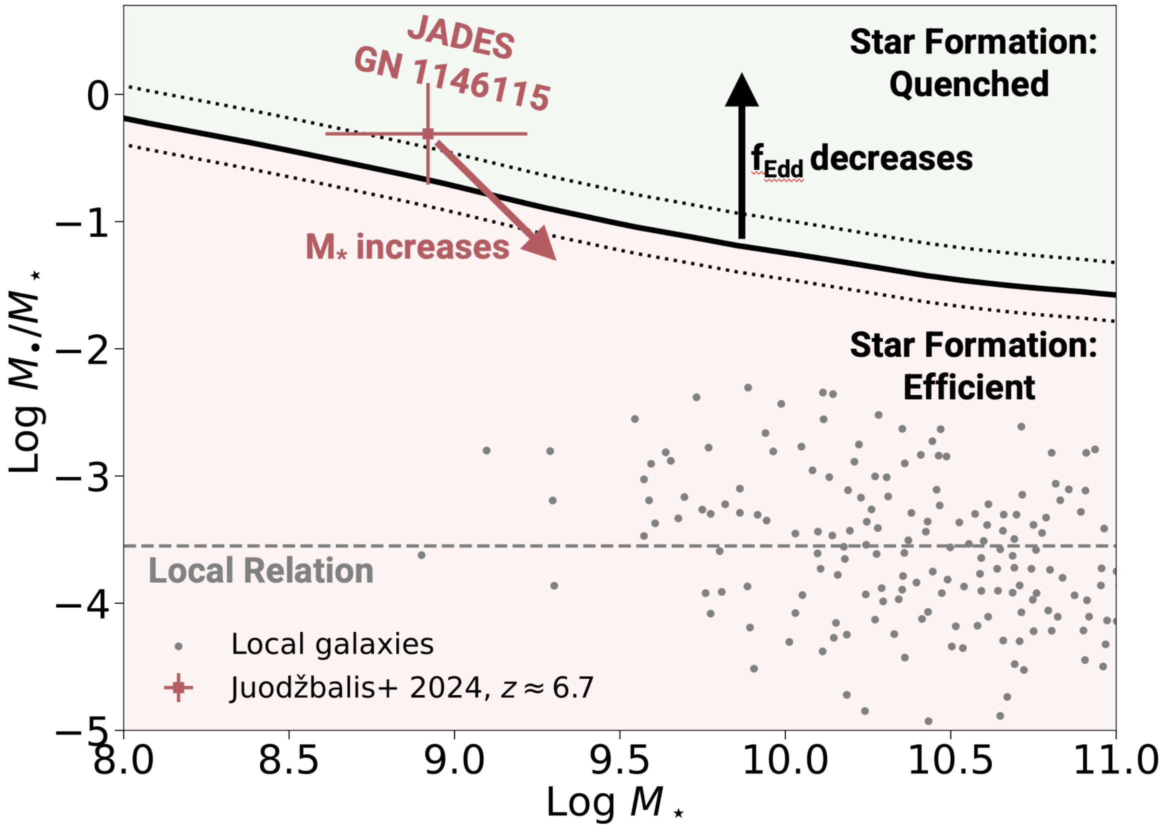

Figure 1. The condition for SMBH-driven star formation quenching developed in Pacucci & Loeb (2024) is applied to the galaxy JADES GN 1146115 (Juodžbalis et al. 2024), shown in the $[M_\star,\ M_\bullet/M_\star]$ plane with its 1σ uncertainties. The dotted lines indicate how the range of $f_{\rm Edd}$ estimated for JADES GN 1146115 affects the threshold on $M_\bullet/M_\star$. Galaxies hosting overmassive black holes in the green area experience reduced star formation as quasar feedback increases the gas temperature above the virial one. Local galaxies on the $M_\bullet - M_\star$ relation (shown as a dashed line) are indicated with gray symbols (Reines & Volonteri 2015). The red arrow indicates the effect of an increasing host's stellar mass in changing the location of the galaxy in the plane; the black arrow indicates the effect of a decreasing $f_{\rm Edd}$ in raising the threshold value of $M_\bullet/M_\star$. Both changes would lead JADES GN 1146115 to a region where star formation is more efficient.

In this Research Note, we directly apply this framework to JADES GN 1146115, an extremely overmassive black hole at $z = 6.7$ (Juodžbalis et al. 2024).

2. RESULTS

JADES GN 1146115 is a compact galaxy ($r_e \approx 140$ pc) of stellar mass $\log(M_\star/\mathrm{M}_\odot) = 8.92^{+0.30}_{-0.31}$, hosting a black hole with mass $\log(M_\bullet/\mathrm{M}_\odot) = 8.61^{+0.27}_{-0.24}$, thus leading to a $M_\bullet/M_\star$ ratio of $\sim 40\%$. Its Eddington ratio is $f_{\rm Edd} = 0.024^{+0.011}_{-0.008}$, with a systematic scatter of 0.5 dex, making it an underluminous, "dormant" SMBH.

For a detailed description of the theoretical model, the interested reader is referred to Pacucci & Loeb (2024). In summary, star formation in a compact, high-z galaxy is quenched if the SMBH injects enough thermal energy into the host to raise its gas temperature above the virial one. Expressing this condition in terms of the ratio $M_\bullet/M_\star$:

$$\frac{M_\bullet}{M_\star} > 8 \times 10^{18} \frac{n\Lambda}{f_{\rm Edd}} \left(\frac{\Omega_b}{\Omega_m} \frac{M_h}{M_\star} - 1 \right) . \tag{1}$$

Here, n is the average gas number density, Λ is the cooling function, Ω_b/Ω_m is the baryon fraction, and M_h is the halo mass. Compared to Pacucci & Loeb (2024), here we only adapt our assumption on $f_{\rm Edd}$. Instead of assuming $f_{\rm Edd} = 1$ (as JWST's overmassive systems are found to have rates $0.1 < f_{\rm Edd} < 5$, see, e.g., Harikane et al. 2023; Maiolino et al. 2023), we use the actual $f_{\rm Edd}$ measured by Juodžbalis et al. (2024), with its 1σ uncertainty: $f_{\rm Edd} = 0.024^{+0.011}_{-0.008}$.

The location of JADES GN 1146115 in the $[M_\star,\ M_\bullet/M_\star]$ plane is shown in Figure 1. In summary, JADES GN 1146115 is at the threshold between regions of efficient and inefficient star formation.

3. INTERPRETATION

JADES GN 1146115 is a galaxy characterized by an instantaneous star formation rate (SFR) of $1.38^{+0.92}_{-0.45}$ $M_\odot$ yr^{-1}, lower by a factor of ~ 3 compared to similar galaxies. Furthermore, this rate has been nearly constant in the last ~ 100 Myr (Juodžbalis et al. 2024). This time scale is intriguingly similar to typical quasar lifetimes, i.e., $10^7 - 10^8$ yr, which is the duration of rapid black hole growth (Hopkins et al. 2005).

Our physical interpretation of the galactic system JADES GN 1146115, based on the Pacucci & Loeb (2024) model, is the following. Its central SMBH grew at high rates for a typical quasar lifetime, overgrowing the stellar content of its host and pushing the galaxy well inside the region in the $[M_\star,\ M_\bullet/M_\star]$ plane where star formation is globally inefficient. Possibly due to a decrease in the stable gas supply, the central SMBH is now in a dormant state, accreting at low levels. The reduced effect of quasar feedback decreases the temperature floor, thus effectively placing the system at the transition boundary in the $[M_\star,\ M_\bullet/M_\star]$ plane. As shown in Fig. 1, two events may eventually push the system deep into the region where global star formation is efficient. First, an additional decrease in the Eddington ratio. Second, a stable (albeit slow) increase in the stellar content of the galaxy; at the current SFR, this galaxy needs ~ 1 Gyr to double its mass (Juodžbalis et al. 2024). Any combination of these events would allow the system to restart efficient star formation, possibly closer to the star-forming main sequence (e.g., Popesso et al. 2023).

In summary, the application of our model to JADES GN 1146115 suggests that we may be witnessing the slow resurgence of efficient star formation in a galaxy that has been dominated by its extremely overmassive black hole in the past ~ 100 Myr.

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