Formation of z~6 Quasars from Hierarchical Galaxy Mergers

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Definitions and Jargon

- QUASAR stands for QUASI-stellAR radio source
- Extremely bright and active nucleus of a young galaxy
- $Z \sim 6 = \text{about 800 million years after Big Bang.}$
- SED - Spectral Energy Distribution
- FIR Galaxy - Far InfraRed Galaxy
- BH / SMBH - Black Hole/ Super Massive Black Hole
Properties of Z~6 Quasar

- Low space density (~$10^{-9}$ MPC$^{-3}$)
- High luminosities ($M_{1450\text{Å}} < -26$)
- Gunn-Peterson absorption troughs in their spectra (places them at the end of the epoch of reionization)
- Lack of evolution in their SED compared to low redshift Quasars
SDS J1148+5251

- Most distant quasar know. Discovered by the Sloan Digital Sky Survey.
- $Z = 6.42$. $M_{1450\text{Å}} = -27.8$
- $L_{\text{bol}} = 10^{14} L_{\text{sun}}$
- $\text{SMBH} = (1-5) \times 10^9 \text{Msun}$
- Near Solar metallicity in Quasar host
Very rare Quasar

- Low abundance of such quasars.
- Hosted by massive halos ($>10^{13} M_{\text{sun}}$) in rare density peaks
- $\Lambda$CDM cosmology suggests that small objects form first and merge - “hierarchical assembly”
- Originates in highly overdense regions in the initial dark matter density distribution.
- Quasar and host form from many gas-rich mergers.
Cosmological Parameters

Wilkinson microwave Anistropy Probe

WMAP1 - (\(\Omega_m = 0.3, \Omega_b = 0.04, \Omega_{\Lambda} = 0.7, h = 0.7, n_s = 1, \sigma_8 = 0.9\))

WMAP3 - (\(\Omega_m = 0.236, \Omega_b = 0.042, \Omega_{\Lambda} = 0.759, h = 0.732, n_s = 0.95, \sigma_8 = 0.74\))

For the purpose of this paper, the simulations used WMAP1 values because WMAP3 predicts lower halo masses and longer formation time. Although they do compare results using WMAP3.
**Little Methodology**

1. Perform a coarse dark matter sim of volume of $1 \, h^{-3} \, Gpc^3$ to find candidate halo for quasar.

2. Largest halo is candidate for formation of quasar at $z = 6.5$

3. “Zoom-in” on candidate region and simulation is rerun with higher resolution
Fig. 1.— Snapshots from a cosmological simulation run with WMAP-like parameters. The images show projected density of dark matter in x-y (left column) and x-z (right column) planes; the red dot represents the center of mass of the quasar halo, which is the largest halo at both $z = 0$ and 6. The top panels show the zoom-in run at $z = 0$. The middle and bottom panels show the zoom-in runs at $z = 6.06$ and 0, respectively; the number at the lower left corner indicates the number of groups identified at that redshift.
Merger Trees

- Traces mergers throughout redshift
- The most massive progenitors at each redshift are traced by tags to identify earlier progenitors
- Groups that contribute >10% of the halo mass at each time step are progenitors
- This will give the history of our suspect quasar
Halo Mass functions from cosmological simulations. 
Coarse Run.
Halo Mass functions from cosmological simulations.
Zoom in Run.
Merging history of the largest halo.
Modeling Mergers major factors

• Major mergers = mass ratio of the merging galaxies are near unity.

• Only the major mergers play the most important role in the formation and evolution of massive galaxies.

• Gas in a rotationally supported disk loses angular momentum through gravitational torques excited by tidal forces in a merger, driving the growth of SMBH. This is most effective in a major mergers.
### Table 1: Progenitor Properties and Numerical Parameters

| Galaxy<sup>a</sup> | Z<sup>b</sup> | $M_{vr}$<sup>c</sup> ($10^{10} h^{-1} M_{\odot}$) | $v_{vr}$<sup>d</sup> (km s<sup>-1</sup>) | $f_{gas}$<sup>e</sup> | $M_{BH}$<sup>f</sup> ($10^5 h^{-1} M_{\odot}$) | $R_p$
<sup>g</sup> ($h^{-1}$ kpc) | $R_0$
<sup>h</sup> ($h^{-1}$ kpc) |
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<td>6.3</td>
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<td>1.0</td>
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<td>5.3</td>
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<td>15.0</td>
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<td>34.5</td>
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<sup>a</sup> Name of galaxy progenitor. G1 is the halo at $z = 14.4$.

<sup>b</sup> Redshift at which the progenitor enters the merger tree.

<sup>c</sup> Virial mass, assuming overdensity $\Delta = 200$.

<sup>d</sup> Virial velocity, assuming overdensity $\Delta = 200$.

<sup>e</sup> Gas fraction of the progenitor baryonic mass.

<sup>f</sup> Progenitor BH mass at the merger redshift.

<sup>g</sup> Pericentric distance of the incoming progenitor to the center of mass of the existing system.

<sup>h</sup> Initial distance of the incoming progenitor to the existing system.
Black Hole seeds

• Need to grow a BH up to $10^9 M_{\text{sun}}$ in less than 800 million years.

• **1. Pair instability PopIII** - BH $\sim 10^2 M_{\text{sun}}$

• 2. Hot, dense clumps of gas collapse to form $\sim 10^6 M_{\text{sun}}$

• 3. $\sim 20 M_{\text{sun}}$ BHs from direct collapse of self-gravitating gas due to global instabilities.

• In simulation - it is necessary for galaxy progenitors to have massive BH seeds ($\sim 10^5 M_{\text{sun}}$)
Escaping BHs?

- When galaxies merge, the BH’s may merge or be ejected by gravitational recoil.
- Depends on: \( V_{\text{esc}} = \sqrt{(2|\Phi[r]|)} \).
Hierarchical Assembly of the Quasar

- Progenitors are very compact and gas rich.
- Strong gravitational interactions between the merging galaxies lead to tidal tails, strong shocks and efficient gas inflow that triggers large-scale starbursts.
- Highly concentrated gas fuels rapid accretion onto the SMBH
- $Z \sim 14-9$, merging systems are small (tens of kiloparsecs). By $Z \sim 9-7$, scale and strength are much greater.
Part 2

- At $Z \sim 6.5$, progenitors galaxies coalesce SMBH accretion and feedback to a climax.
- This feedback introduces a powerful wind that clears the material around the quasar.
- The largest SMBH appears as an optically bright quasar. After this, the quasar feedback quenches star formation and quasar activity dies down.
Star formation

- As progenitors undergo strong interactions, stars form rapidly.
- Total SFR: 100 to $> 10^4 \, M_{\text{sun}}/\text{year}$
- By $Z < 7$, SFR decreases gradually due to depletion of gas supply and strong feedback
- By $Z \sim 6.5$, SFR: $\sim 100 \, M_{\text{sun}} / \text{year}$ (order of mag lower than J1148+5251)
Metallicities

- Rapid star formation produces an abundant mass of heavy elements.
- Dips and jumps are due to new material mergers.
- Metals are widespread due to outflows.
Some regions are supersolar metallicity. Due to infalling material triggering small scale star formation.
Growth of SMBH

- Total BH accretion rate grows steadily during assembly.
- Eddington ratio: $\frac{L_{\text{bol}}}{L_{\text{edd}}} \left(3.3 \times 10^4 \frac{M}{M_{\odot}} \times L_{\odot}\right)$
- Although each BH may not accrete at Eddington rate, so growth of quasar is a collective contribution of each BH.
Escaping BHs?

• Emission of gravitational waves carries away linear momentum, could cause BH to recoil.
• If recoil velocity is greater than escape velocity, BH escape.
• But, simulation shows that recoil/kick velocity is much smaller than escape velocities
Evolution of total BH and stellar mass.
Quasar Luminosities

- $L_{\text{bol}} = \varepsilon_r M c^2, \varepsilon_r = 0.1$
- If BHs are spinning, $L$ is increased by a factor of 4.
- Host appears as an ultraluminous infrared galaxy (ULIRG) $L_{\text{bol}} > 10^{12} L_{\text{sun}}$
Quasar lifetimes

\[ \tau_{q50} \text{ (Myr)} \]

Limiting \( L_{B,\text{min}} (L_\odot) \)
Feedback from Starburst Driven wind

- Same simulation run, but at lower resolution and wind model.
- Effect of wind on quasar evolution is minor.
Number of such Quasars

- Depends on cosmological constants used.
- WMAP1 ~ 36
- WMAP3 ~ handful
- WMAP3 will produce fewer luminous quasars
Era of Reionization

- WMAP3 results - universe was 50% ionized at $Z \sim 9.3$
Summary

- Find target halo by performing a N-body simulation in large volume.
- Largest halo reaches $M \sim 5.4 \times 10^{12} \text{h}^{-1} \text{Gpc}^3$ through 7 major mergers between $Z \sim 14.4$ and $Z \sim 6.5$
- Quasar host galaxy build rapidly through gas rich mergers.
- SFR up to $10^4 \text{M}_{\odot}/\text{year}$
- Reaching stellar mass of $10^{12}\text{M}_{\odot}$ at $Z \sim 6.5$
- BH accretion reaches $20 \text{M}_{\odot}/\text{year}$ and $M = 2 \times 10^9 \text{M}_{\odot}$
- At peak, this is consistent with J1148-5251