The Formation of the First Supermassive Black Holes

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Collaborators:

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**Observational puzzle: z>6 quasar BHs**

- Rare ("5σ") objects:
  - 10 found in SDSS at z>6
  - 20 in CFHQS + few others

- Record: z = 7.085 (t=0.77 Gyr, UKIDDS)

- Tip of the iceberg (?):
  - Space density \( \sim 1 \) Gpc\(^{-3}\)

- Mass estimates
  - \( M_{\text{bh}} = \frac{L_{\text{obs}}}{L_{\text{Edd}}} \approx 10^{9-10} \) M\(_{\odot}\) (Eddington luminosity)
  - \( M_{\text{halo}} \approx 10^{12-13} \) M\(_{\odot}\) (Matching space density)

Willott et al. (2010)
Formation and Signatures

of the First

Stars and Quasars

Zoltan Haiman

with: A. Loeb
M. Rees
A. Thoul

Contacts with observations

logIMF

III. II. I.

3M_☉ 8M_☉

logM

I. Effects on CMB
   Reionization  CMB Anisotropy Damping
   \( \tau < 1 \) (Scott, Silk & White 1995)
   \( \tau \sim 0.1 \) MAP + Planck
   \( \tau \sim 0.01 \) polarization (Zaldarriaga & Seljak)
   UV flux + dust  Spectral Distortion
   \( y(\text{Compton}) < 1.5 \times 10^3 \) (Fixsen et al)

II. Carbon Enrichment
   Z~0.01Z_☉

III. Machos
   \( <M> \sim 0.5 M_☉ \)
   \( M_{\text{tot}} \sim 2 \times 10^{11} M_☉ \) (Alcock et al 1996)
Dear Zoltan,

I retrieved your recent preprint on reionization from the astro-ph archive and read through it. It looks very interesting, and seems to be the first effort to put together cosmology and star formation to calculate things like reionization.

[...]

Clearly, what one assumes about star formation and the stellar IMF at early times is of great importance.

[...]

I am interested in your paper because I have been interested in the possibility of the formation of large numbers of massive metal-free "Population III" stars at large redshifts. I expect the mass scale for star formation to be shifted toward larger masses at earlier times because I think that typical stellar masses should scale with the Jeans mass in collapsed pre-galactic objects or primeval galaxies, and all reasonable estimates give larger Jeans masses at earlier times. In some cosmological scenarios such as a baryonic universe, a lot of mass could have gone into very massive stars at large redshifts, possibly ending up in black holes that contribute to the dark matter. However, in order for the resulting black hole masses not to be too large, cooling below 10^4 K is necessary, and hence the possibility of H2 cooling is of interest.

[...]

Best regards, Richard B. Larson.
“Maximum” SMBH Masses

Masses estimated from: Fan et al. (2006); Willott et al. (2010); Mortlock et al. (2011)

e-folding (Edd) time:
$$M/(dM/dt) = 4 (\varepsilon/0.1) 10^7 \text{yr}$$

Age of universe ($z=6-7$)
$$(0.8 - 1) \times 10^9 \text{yr}$$

Must start early!

Accretion rate must keep up w/ Eddington most of the time

$\text{Obvious alternatives:}$
1. merge many BHs
2. grow faster

Masses estimated from: Fan et al. (2006); Willott et al. (2010); Mortlock et al. (2011)
"Stellar seed" vs "direct collapse"

**STELLAR SEEDS**
uninterrupted near-Eddington accretion onto \( \sim 10-100 \, M_\odot \) seeds
- continuous gas supply
- avoid radiative feedback depressing accretion rate
- must avoid ejection from halos and loosing BHs
- avoid overproducing total \( \rho_{BH} \) (in \( \sim 10^6 \, M_\odot \) holes)

**DIRECT COLLAPSE (A.K.A “HEAVY SEEDS”)**
rapid formation of \( 10^5-10^6 \, M_\odot \) black holes at \( z>10 \) by direct collapse of gas or via intermediary (supermassive star, quasi-star, or ultra-dense star cluster)
- gas must be driven in rapidly (deep potential)
- transfer angular momentum
- must avoid fragmentation
- avoid cooling via \( H_2 \) to \( T \sim \text{few } 100 \, K \) and fragmenting
Growing SMBHs by Accretion + Mergers

$z \approx 6$

$M_{bh} = \text{few } \times 10^9 M_\odot$

$M_{halo} = \text{several } \times 10^{12} M_\odot$

$M_{halo} \approx 10^6 M_\odot$

$\nu_{esc} \approx \text{few km/s}$

“Merger trees”: Haiman & Loeb (2001); Haiman (2004); Yoo & Miralda-Escude (2004); Sesana et al. (2004); Bromley et al. (2004); Volonteri & Rees (2006), Shapiro (2005); Tanaka & Haiman (2009), Volonteri & Natarajan (2010), ...

Hydro simulations: Li et al. (2007); Pelupessy et al. (2007); Sijacki et al. (2009); Bellovary et al. (2011), di Matteo et al. (2012), ...
Making the $\sim 10^9 M_\odot$ SMBHs

Tanaka, Perna & Haiman (2012)

$10^9 M_\odot$ BHs from unusually massive ($10^2 M_\odot$) runaway early seeds ($z>20$) that avoided ejection at merger: asymmetric mass ratio $q<0.01$
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Exponential ($f_{\text{duty}} = 0.5$)

Bondi-limited ($f_{\text{duty}} = 0.8$)

Local SMBH Mass density: $\rho_{\text{tot}} \approx 4 \times 10^5 M_\odot \text{Mpc}^{-3}$
Eliminating unwanted $\sim 10^6 M_\odot$ BHs
(without suppressing most massive ones)

- Internal feedback:  
  - $M_{BH}$ limited in each halo by $M_{BH} - \sigma$ relation  
  (e.g. Volonteri & Natarajan 2010)

- No BH seeds after PopIII $\rightarrow$ PopII?  
  - Requires sharp cut at $z \sim 25$ and low $f_{\text{seed}} \sim 10^{-3}$  
    (mutually exclusive…)
  (Tanaka & Haiman 2009)

- External radiation backgrounds:  
  - stars and their BH remnants build early IR/UV/X-ray
  - affect $H_2$ chemistry, heat IGM
  (Tanaka et al. 2012)
Self-regulation by X-ray “Global Warming”

Total BH mass density remains below 10% of its present-day value
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It appears “global warming” is now the most potent force in the universe, according to a scientist from the Max Planck Institute for Astrophysics. An actual scientific paper preprint published in the Cornell University science archive makes the connection to black holes in the title, and includes “climate change” in the abstract.

Sigh. It isn’t even past coffee on Sunday morning and already we have our winner. This one... is weapons grade stupidity. I would not believe that a scientist from a prominent research institute could utter such a statement had I not read it in a prominent science magazine. It’s another “Vinerism” in the making: Children just aren’t going to know what black holes are.

It immediately reminded me of the famous line uttered by Tom Cruise in the movie a A Few Good Men:

“Should we or should we not follow the advice of the galactically stupid!”

But then again, this is The New Scientist. Read on, emphasis mine.

...  

Something must have limited the growth of these black holes. Now Takamitsu Tanaka at the Max Planck Institute for Astrophysics in Garching, Germany, and colleagues have a climate-based explanation.

...

Black holes need cool gas to grow so this would have slowed down the growth of other black holes in smaller protogalaxies, even as the growth of black holes in the most massive protogalaxies continued apace (arXiv.org/abs/1205.6467v1).
“Stellar seed” vs “direct collapse”

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  - continuous gas supply
  - avoid radiative feedback depressing accretion rate
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• **DIRECT COLLAPSE**
  rapid formation of 10\(^5\)-10\(^6\) M\(_\odot\) black holes at z>10 by direct collapse of gas or via intermediary (supermassive star, quasi-star, or ultra-dense star cluster)
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  - *avoid cooling via* \(H_2\) *to* \(T \sim\) few 100 K
How to avoid cooling/fragmentation?

- In “minihalos” gas cools and forms PopIII stars
- In “$T_{\text{vir}} > 10^4 \, \text{K}$” halos (with no prior PopIII starformation), gas cools via Ly$\alpha \rightarrow$ high density $\rightarrow$ H$_2$ cooling $\rightarrow$ $M_{\text{acc}} \propto c_s^3 \sim 10^{-2} \, M_\odot \, \text{yr}^{-1}$
  similar to popIII!

Omukai, Schneider & Haiman (2008)

To avoid this fate, gas must get to ‘safe zone’ at $n > n_{\text{crit}} > 10^4 \, \text{cm}^{-3}$

- Destroy H$_2$ with huge LW flux: $J_{21}(\text{crit}) \approx 10^4$
- Shock in dense $n > 10^4 \, \text{cm}^{-3}$ core: $v_s(\text{crit}) \approx 10 \, \text{km/s}$
- Heat gas by primordial magnetic field: $B(\text{crit}) \approx 3 \, \text{nG}$
- Trap Ly$\alpha$ radiation for a free-fall time (high $n_{\text{HII}}$ & $N_{\text{HII}}$)

Shang et al. (2010)
Inayoshi & Omukai (2012)
Sethi & Haiman (2010)
Silk & Spaans (2008)
Self-Shielding of H$_2$ Lyman Werner lines

Wolcott-Green, Haiman & Bryan (2011)

- Critical for SMBH formation:
  \[ f_{\text{shield}} = J(N_{H_2})/J(N_{H_2}=0) \approx \text{several} \times 0.01 \]

- Two-step process: \[ H_2 + \gamma \rightarrow H_2^{(*)} \rightarrow H + H + \gamma' \]

- Radiative transfer must be followed for O(10) lines in ground state; dozens at T=few \times 1000 \text{ K}

- Also: anisotropic density, velocity, temperature gradients

→ Previous works assume optically thin gas, or (mis)use local \( N_{H_2} \) with \( f_{\text{shield}}(N_{H_2}) \) from Draine & Bertoldi 1996

\[ J(\text{crit}) \text{ reduced by a factor of } >10 \text{ to } J_{\text{crit}} \approx 10^3 \]

Achieved in close (~10kpc) pairs of 10$^8$ M$_\odot$ halos Dijkstra et al. (2009)
Mass of Central Object

Shang, Bryan & Haiman (2010)

10^2 \ M_\odot, Pop III star  
10^5 \ M_\odot, supermassive star/BH  

Abel et al.; Bromm et al.; Yoshida et al.
Ionizing shocks in dense halo core?

- Gas directly heated up into ‘safe zone’  
  Inayoshi & Omukai (2012)
- Look for shocks in core with Mach number > 3-4  
  Fernandez, Bryan & Haiman (2012)
Ionizing shocks in dense halo core?

Fernandez, Bryan & Haiman (2012)
Conclusions

1. Growing z>6 SMBHs with $\sim 10^9 M_\odot$ requires extreme assumptions:
   
   (i) stellar seeds grow at Eddington rate without interruption, or
   
   (ii) rapid “direct collapse” in rare special environments with no metals

2. Extra challenge (i): not to overproduce number of $\sim 10^{5-6} M_\odot$ SMBHs.
   
   → seed formation AND growth are suppressed by X-ray “global warming”

3. Extra challenge (ii): not to cool by H$_2$ and fragment.
   
   → requires large Lyman-Werner flux ($J_{21} \sim 10^3$), achieved in close halo pairs

4. Future Observations:
   
   faint-end quasar LF (optical/radio/X-ray) to $\sim 10^{5-6} M_\odot$ (e.g. JWST)
   
   GWs from eLISA up to $\sim 100$ merger events/yr
   
   smooth reionization topology (e.g. 21cm, kSZ) to diagnose X-rays
Le Fin