Probing the End of Dark Ages with High-redshift Quasars

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High-redshift Quasars and the End of Cosmic Dark Ages

- Existence of SBHs at the end of Dark Ages
- BH accretion History in the Universe?
- Relation of BH growth and galaxy evolution?
- Probing the end of reionization?

Resolved CO emission from z=6.42 quasar

Evolution of Quasar Density

Detection of Gunn-Peterson Trough
Exploring the Edge of the Universe

New z\~7 galaxies
Courtesy of Arizona graduate students
The Highest Redshift Quasars Today

- $z>4$: >900 known
- $z>5$: >50
- $z>6$: 8
- SDSS i-dropout Survey:
  - By Spring 2004: 6000 deg$^2$ at $z_{AB}<20$
  - Sixteen luminous quasars at $z>5.7$
  - Five in the last season
- 30 – 50 at $z\sim6$ expected in the whole survey
Outline

• The Earliest Quasars and Supermassive Massive Black Holes
  – Evolution of z>6 quasars
  – Chemical Enrichment in the Quasar Environment
  – Co-evolution of Supermassive BHs and host galaxies at z~6

• The End of Reionzation
  – G-P troughs in the highest redshift quasars
  – Inhomogeneous reionization

• Collaborators: Strauss, Schneider, Richards, Gunn, Becker, White, Rix, Pentericci, Walter, Carilli, Cox, Omont, Brandt, Vestergaard, Eisenstein, Cool, Jiang, plus many SDSS collaborators
17,000 Quasars from the SDSS Data Release One
Quasar Density at $z \sim 6$

- From SDSS i-dropout survey
  - Density declines by a factor of $\sim 40$ from between $z \sim 2.5$ and $z \sim 6$
- Cosmological implication
  - $M_{\text{BH}} \sim 10^{9-10} \, M_{\odot}$
  - $M_{\text{halo}} \sim 10^{12-13} \, M_{\odot}$
  - 5-6 sigma peaks at $z \sim 6 \rightarrow$ number density consistent with CDM prediction with reasonable duty cycle and M-sigma assumptions
  - not a problem for structure formation as far as DM is concerned

- How to form assemble such massive BHs and “mature” galaxies in less than 1Gyr??
  - The initial assembly of both gal and BH must start at $z \gg 10$
  - Implication on (lack of negative?) feedback for the formation of these monsters?
The Lack of Evolution in Quasar Intrinsic Spectral Properties

- Rapid chemical enrichment in quasar vicinity
- High-z quasars and their environments mature early on
Chemical Enrichment at $z \gg 6$?

- Strong metal emission $\rightarrow$ consistent with supersolar metallicity
- NV emission $\rightarrow$ multiple generation of star formation from enriched pops
- Fe II emission $\rightarrow$ could have Pop III contribution
- Question: what exactly can we learn from abundance analysis of these most extreme environment in the early universe?

Barth et al. 2003

Fan et al. 2001
Early Growth of Supermassive Black Holes

Vestergaard 2004

Dietrich and Hamann 2004

Lack of spectral evolution in high-redshift quasars $\rightarrow$ quasar BH estimate valid at high-z

- Billion solar mass BH indicates very early growth of BHs in the Universe
Sub-mm and Radio Observation of High-z Quasars

- Probing dust and star formation in the most massive high-z systems
- Using IRAM and SCUBA: ~40% of radio-quiet quasars at $z>4$ detected at 1mm (observed frame) at 1mJy level
  → submm radiation in radio-quiet quasars come from thermal dust with mass $\sim 10^8 M_{\odot}$
- If dust heating came from starburst
  → star formation rate of 500 – 2000 $M_{\odot}$/year
  → Quasars are likely sites of intensive star formation

![Graph: FIR flux vs. redshift](image)
Submm and CO detection in the highest-redshift quasar:

- Dust mass: $10^8 - 10^9 M_{\text{sun}}$
- $H_2$ mass: $10^{10} M_{\text{sun}}$
- Star formation rate: $10^3/\text{yr}$

$\Rightarrow$ co-formation of SBH and young galaxies

**CO 3-2 (VLA), 6-5, 7-6 (PdBI)**

Walter, Bertoldi, Carilli et al. 2003, Nature
Bertoldi, Cox, Neri et al. 2003, A&A Let
High-resolution CO Observation of z=6.42 Quasar

- **Spatial Distribution**
  - Radius $\sim 2$ kpc
  - Two peaks separated by 1.7 kpc

- **Velocity Distribution**
  - CO line width of 280 km/s
  - Dynamical mass within central 2 kpc: $\sim 10^{10}$ $M_{\odot}$
  - Total bulge mass $\sim 10^{11}$ $M_{\odot}$
    < M-sigma prediction

- **BH formed before complete galaxy assembly?**
Searching for Gunn-Peterson Trough

• Gunn and Peterson (1965)
  – “It is observed that the continuum of the source continues to the blue of Ly-\(\alpha\) (in quasar 3C9, \(z=2.01\))”
  – “only about one part of \(5\times10^6\) of the total mass at that time could have been in the form of intergalactic neutral hydrogen”

• Absence of G-P trough \(\Rightarrow\) the universe is still highly ionized
A brief cosmic history

 rekombination

 Cosmic Dark Ages: no light no star, no quasar; IGM: HI

 First light: the first galaxies and quasars in the universe

 Epoch of reionization: radiation from the first object lit up and ionize IGM : HI → HII

 HII regions overlap, reionization completed, the universe is transparent and the dark ages ended

 today
Increasing Ly$\alpha$ absorption with redshift:

$z_{\text{abs}}$  $f_{\text{obs}}/f_{\text{con}}$

$\sim5.5$  0.10
$\sim5.7$  0.05
$\sim6.0$  $<0.002$

Zero flux over 300Å immediately blueward of Ly$\alpha$ emission in z=6.28 quasar → Detection of complete Gunn-Peterson Trough: $\tau>>1$ over large region of IGM

Becker et al. 2001
Strong Evolution of Gunn-Peterson Optical Depth

Transition at $z \approx 5.7$?

Fan et al. 2004
Evolution of Ionizing Background

- Ionizing background estimated by comparing with cosmological simulations of Lyman absorption in a LCDM model
  - Ionizing background declines by a factor of >25 from $z \approx 3$ to $z \approx 6$
  - Indication of a rapid decline at $z > 5.7$?
  - The end of reionization – overlapping of individual HII regions – at $z \approx 6$

Fan et al. 2002, 2004
Line of Sight Difference…
Gunn-Peterson Troughs in the Highest-redshift Quasars

- Five quasars known at $z>6.1$
- Strong, complete Ly$\alpha$ and Ly$\beta$ absorption in all five objects immediately blueward of Ly$\alpha$ emission…
- But LOS variation is significant
  - The “last transmitting” redshift ranges from 5.85 to 6.15
  - Patchy reionzation?
  - Non-uniform radiation field?
  - Gradual transition to neutral?
Constraining the Reionization Epoch

- Neutral hydrogen fraction
  - Volume-averaged HI fraction > 0.1% at $z \sim 6$
- From G-P alone:
  - There is still a long way to go from $\tau > 10$ to $\tau \sim 100,000$
  - Gunn-Peterson test only sensitive to small neutral fraction and saturates at large neutral fraction
  - Was H 50% neutral at $z \sim 6.5$ or $z \sim 8.5$ or $z \sim 15.5$? With what scatter? Need powerful test, e.g. HII region, damping wing, LAE…
  - Combined with WMAP results → a more complex reionization history?

Fan et al. in prep
Summary

• **Quasar Luminosity Function**
  – Strong evolution from z~3 to 6

• **Quasar spectral evolution**
  – Quasar environment matured very early, with rapid chemical enrichment
  – $10^{10}$ M$_{\text{sun}}$ BH existed at z>6

• **Radio and sub-mm probes of host galaxies**
  – High-redshift quasars are sites of spectacular star-formation: 1000 M$_{\text{sun/yr}}$
  – First resolved z~6 host galaxy: BH growth before galaxy assembly?

• **Reionization**
  – Neutral fraction rises dramatically at z>5.7
  – Marking the end of reionization
  – But with considerable scatter
  – A complex reionization history?