SDSS Quasar Science

as told by Gordon Richards (Drexel University)

With thanks to the members of the Quasar Working Group, particularly Don Schneider, Xiaohui Fan, Michael Strauss, Pat Hall, Dan Vanden Berk, Sebastian Jester, and Scott Anderson, also Adam Myers
Survey Properties

• 100,000 quasars in 7470 sq. deg. of spectroscopy (DR7; Schneider et al. 2009)
  – i=19.1 for z<3; i=20.2 for z>3
  – <z>=1.5
  – ~50 with z>5 (z_{max}=5.41)

• ~1,000,000 photometric quasars in 8417 sq. deg. of imaging (Richards et al. 2008)
  – up to 95% classification accuracy
  – photo-z’s accurate to 0.3 80% of the time.
Quasar Definition

- “An actively accreting super-massive black hole found in the centers of massive galaxies”
- Quasar = QSO = Active Galactic Nucleus = AGN

(Urry & Padovani 1995)
Some History

- Schmidt (1963, Nature, 197, 1040) Quasars “discovered”; 3C 273 z=0.16 (t=-2Gyr)
- Greenstein & Matthews (1963, Nature, 197, 1041) 3C 48 z=0.37 (t=-4Gyr)
- Before SDSS, z=4.897 (PC 1247+3406; SSG91)
- z=5 in 1999 (t<10%; SDSSp J0338+0021; Fan et al.)
- z=6 in 2001 (t<1Gyr; SDSS J1030+0524; Fan et al.)
- z=6.43 in 2003 (SDSS J1148+5251; Fan et al.)
- Current record holder, z=6.43 (Willott et al. 2007; CFHQS J2329-0301)
Some History

- Schmidt (1963, Nature, 197, 1040) Quasars “discovered”; 3C 273 z=0.16 (t=-2Gyr)
- Greenstein & Matthews (1963, Nature, 197, 1041) 3C 48 z=0.37 (t=-4Gyr)
- Before SDSS, z=4.897 (P99)
- z=5 in 1999 (t<10%; SDSS, al.)
- z=6 in 2001 (t<1Gyr; SDSS, al.)
- z=6.41 (Willot et al. 2003)
- Current record holder, z=7.51 (CFHQS J2329-0301)
The Gunn-Peterson (1965) Effect

Density of neutral hydrogen (from absorption) lower than expected. Lots of hydrogen gas in the Universe; it should absorb most of the photons blueward of 1216 Angstroms. The spectrum should really look like this.

Universe became re-ionized between $z=1100$ and $z=2$?
Searching for the Epoch of Re-ionization

The z>6 SDSS quasars show the expected GP absorption trough.

Combining results from WMAP suggest that there may even have been 2 epochs of re-ionization.

See the review by Fan, Carilli, & Keating (2006, ARAA)

Quasar Evolution

- The intrinsic properties of quasars have changed relatively little over cosmic time.

![Graph showing redshift versus intensity](image)

Fan et al. 2004, 2008

Vignali et al. 2005;
Shemmer et al. 2005
Quasar Evolution

- Quasar themselves may not have evolved much over time.
- But their space density has.
- SDSS sample first to probe all redshifts at once.

Richards et al. 2006
Quasar Evolution: Cosmic Downsizing

- Even this picture has changed radically in the past 10 years.
- Cowie et al. 1996 “cosmic downsizing”.
- First seen in AGNs in Ueda et al. 2003.
- Can’t see in the optical due to lack of dynamic range in luminosity.

Ueda et al. 2003

\[ \text{log}(L_x) \]

\[ \log(\phi[M_\text{I}(z=2)]) \text{ [Mpc}^{-3} \text{mag}^{-1}] \]

\[ z=1.63 \]

\[ M_\text{I}(z=2) \]

2–10 keV

Redshift
Downsizing in the Optical

- First robust evidence of cosmic downsizing of quasars in the optical to be presented by Croom et al. (2008)
- Part of the joint SDSS+2dF (2SLAQ) effort

Croom et al. 2008
Quasars and Cosmic Downsizing

• Previous speakers have already gone over downsizing in general.
• Let’s look at how quasars fit in.
• Previously: galaxy and quasar people lived in different worlds.
• Today:
  – Most massive galaxies host supermassive BHs
  – Have gone through a quasar phase
The $M_{\text{BH}}$-sigma Relation

Massive black holes co-evolve with their host galaxies.

(Tremaine et al. 2002; also Ferrarese & Merritt 2000; Gebhardt et al. 2000; Magorrian et al. 1998)
Soltan (1982) Argument

- The current black hole mass density roughly matches that expected from accretion in quasars over cosmic time (assuming ~10% efficiency).
- N.B. High efficiency requires spinning black holes.

The inferred accretion rate depends on the fraction of obscured quasars.

Yu & Tremaine 2002; Shankar, Weinberg & Miralda-Escude 2007
Type 2 (Obscured) Quasars

- Thought to exist for a long time
  - By symmetry arguments with Sy1/Sy2
  - To explain the X-ray background.
- First large samples came from the SDSS (Zakamska et al.)

Type 1 Composite (Vanden Berk et al. 2001)

Type 2 Composite (Zakamska et al. 2003)
Luminosity Dependent Obscuration?

- The obscured fraction appears to be dependent on luminosity (ranges from 1:1 to 4:1)
- Luminous quasars: ~1/3 each are unobscured, self-obscured, host-obscured (Polletta et al. 2008)

Ueda et al. 2003
Reyes et al. 2008
Quasar Clustering

- Some of the most powerful results come from clustering analyses.
- Quasars are more clustered on small scales than large scales.
- Comparing with models of dark matter clustering gives the "bias" (overdensity of galaxies to DM)
- Linear bias ($b_q=1$) ruled out at high significance.

Myers et al. 2007
Clustering Results

Age of the Universe (Gyr)

- SDSS DR5Q (uni)
- SDSS photo-z
- 2QZ
- SDSS z>2.9
- LBGs

- Uniform growth to z~2
- Efficient Feedback
- Maximal Growth

Ross et al. (2008)
Quasars Have $\sim$ Constant Mass?

- Can turn estimates of $b_Q$ into mass of halos hosting quasars.
- Find very little evolution in halo mass with redshift.
- Mean halo mass $3-8 \times 10^{12} h^{-1} M_{\odot}$ (Myers et al. 2007; Croom et al. 2005; Porciani et al. 2004).
- Shen: extends to $z=4$

Myers et al. 2007
What We (Used To) Expect

1. Galaxies (and their DM halos) grow through hierarchical mergers
2. Quasars inhabit rarer high-density peaks
3. If quasars long lived, their BHs grow with cosmic time
4. $M_{BH}-\sigma$ relation implies that the most luminous quasars are in the most massive halos.
5. More luminous quasars should be more strongly clustered (b/c sample higher mass peaks).
What We Get

1. Galaxies (and their DM halos) grow through hierarchical mergers, but with “cosmic downsizing”
2. Quasars always turn on in potential wells of a certain size (at earlier times these correspond to relatively higher density peaks).
3. Quasars turn off on timescales shorter than hierarchical merger times, are always seen in similar mass halos (on average).
4. $M_{BH}-\sigma$ relation then implies that quasars trace similar mass black holes (on average).
5. Thus little luminosity dependence to quasar clustering (L depends on accretion rate more than mass).
6. Observed range of luminosity is thus due to a range of accretion rates and not mass.
Merger Scenario w/ Feedback

- Merge gas-rich galaxies, forming buried quasars, feedback expels the gas, revealing the quasar and eventually shutting down accretion.
- Feedback from: jets, radiation, accretion disk winds

Hopkins et al. 2005
Clouds (and Torus?) $\Rightarrow$ Disk Winds

Urry & Padovani 1995

Proga 2005
Emission Lines as Wind Diagnostics

- Disk winds are thought to be the reason why the broad lines are single peaked (Murray et al. 1995)
- Investigating line properties as a function of luminosity, color, etc. tell us something about the inner structure of the quasar.

Richards et al. 2002
Broad Absorption Line Quasars

- Similarly, quasars with P-Cygni like absorption troughs reveal much about the nature of the accretion disk wind.

- Weak X-ray (relative to UV) allows stronger winds.

Hall et al. 2002; Reichard et al. 2003a,b; Tolea et al. 2003; Trump et al. 2006; Gibson et al. 2008
All Quasars Are Not the Same
The two necessary ingredients ... are a massive black hole and an abundant fuel supply ... The combination is rare today, but evidently was not so at high redshift.” (Kauffmann et al. 2003)

Seyferts:
Less massive BHs, actively growing, brief breakout of accretion emission, relatively young stellar population

LINERS:
Massive BHs, masive hosts, long life-time, minimal accretion, fuel exhausted, older stellar population
The Future

• As much good quasar science remains to be done with the SDSS data as has already been done.
• Stripe 82 holds much promise as a pre-LSST data set.
• As multi-wavelength coverage in the SDSS area grows, so will the science.
If no obscured quasars, the X-ray background should be flat (consistent with the sum of individual sources).
Quasars accreting over a wide range of luminosity must be driven by a narrow range of black hole masses. This implies that a wide range of quasar luminosities will then occupy a narrow range of $M_{\text{BH}}$. 

Lidz et al. 2006
Wytithe & Loeb 2003

Expect QLF to look like dark matter halo distribution. But, quasar (and star formation) shuts off if feedback greater than binding energy in a dynamical timescale.

Break due to “inability of gas to cool inside massive dark matter halos”?
Gallagher et al. 2002

Proga 2005

Konigl & Kartje 1994;
EvereX 2006
Spitzer Warm Mission

![Graph showing data points and curves for various datasets such as XFLS, Bootes, 2MASS, SDSS, SDSS z<3 QSO, and GALEX, with annotations for redshifts z=0.5, z=1.5, and z=2.5.](image)
Re-ionization References

- Fan et al. 2001, “A Survey of z>5.8 Quasars in the SDSS. I. Discovery of Three New Quasars at z~6”, AJ, 122, 2833 (355 cites)
- Wyithe & Loeb 2003, “Reionization of Hydrogen and Helium by Early Stars and Quasars”, 586, 693 (130 cites)
• Testing White vs. Black text. I like the black, but white may work better. Who knows?
• What about yellow or maybe even a color like blue?
• Melanie really likes pink.
• Rapid chemical enrichment in quasar vicinity
• Quasar env has supersolar metallicity : no metallicity evolution
• High-z quasars are *old, not yet first quasars.*
• Needs to push to $z \sim 7$
Quantify clustering: $\xi(r)$ or $w(\theta)$
- probability of two galaxies separated by $r$ (or $\theta$).
- relative to a random unclustered distribution
- large on small scales, small on large scales

$\textbf{bias} = \text{galaxy clustering} / \text{dark matter clustering}$
All Quasars Are Not the Same

Elvis 2000

Richards et al. 2006

MHD Dominated ⇒ Line Driven Dominated
Survey Properties

- **100,000 quasars in 7470 sq. deg. of spectroscopy** (DR7; Schneider et al. 2009)
  - $i=19.1$ for $z<3$; $i=20.2$ for $z>3$
  - $<z>=1.5$
  - $\sim 50$ with $z>5$ ($z_{\text{max}}=5.41$)
- **$\sim 1,000,000$ photometric quasars** in deg. of imaging (Richards et al. 2006)
  - up to 95% classification accuracy
  - photo-z’s accurate to 0.3 80%