Quasar Surveys and Luminosity Functions

Gordon Richards
Drexel University

With thanks to Michael Strauss, Don Schneider, Pat Hall, Dan Vanden Berk, Mark Lacy, Sebastian Jester, Chris Stoughton, Xiaohui Fan, Bob Nichol, Alex Gray, Robert Lupton, Scott Croom, Alex Szalay, Don York and the SDSS Collaboration
Quasar Luminosity Function

\[ \rho(z, M_i < -27.6) \text{ (Mpc}^{-3} \text{)} \]

- SDSS binned
- SDSS ML fixed
- SDSS ML var
- 2QZ
- SSG95
- Fan+01
- Fan+04

- \( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1} \)
- \( \Omega_m = 0.3 \)
- \( \Omega_{\Lambda} = 0.7 \)

Croom et al. 2004

e.g., Richards et al. 2006
Space density of quasars as a function of redshift and luminosity

Typically fit by double power-law

\( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1} \)
\( \Omega_m = 0.3 \quad \Omega_{\Lambda} = 0.7 \)

\( \Phi(M_b) \) (Mpc\(^{-3}\) mag\(^{-1}\))

Croom et al. 2004
Number of quasars is changing as a function of time.
Space density of quasars is constant. Brightness of individual quasars is changing.
Number of quasars is changing as a function of time, as a function of luminosity.
Luminosity-Dependent Density Evolution

AKA:

Comsic Downsizing

Ueda et al. (2003)
Luminosity Dependent Obscuration?

Ueda et al. 2003

Elvis 2000
Comparison with Merger Models

Merge gas-rich galaxies, forming buried quasars, feedback expels the gas, revealing the quasar and eventually shutting down accretion.

Hopkins et al. 2005
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”?
Recent Progress: The SDSS QLF

SDSS, though relatively shallow, allows us to determine the QLF from $z=0$ to $z=5$ with a single dataset.

QLF slope flattens at high-$z$. Not PDE, PLE

Richards et al. (2006)
• There are no quasars with intrinsically faint peak luminosities; such objects are merely in transition.

• The change of the bright slope in the QLF at high redshift means the distribution of intrinsic luminosities is broader at high redshift.

Hopkins et al. 2005

Richards et al. 2006
A Caveat: Jiang et al. 2007

z=6 QLF not flat? (Or steepens again after flattening?)

Fontanot also argue that z~4 flatness is instead due to selection function correction.
Optimizing Quasar Surveys

X-ray/IR surveys can probe very deep and find obscured quasars. They reveal densities up to a few 1000 per square degree.

Optical surveys are generally much shallower and miss obscured quasars. Densities are ~150 per square degree.

Need deeper optical surveys and/or larger area X-ray/IR surveys.
Quasar Surveys Status
Quasar Surveys Status

Hasinger et al. 2005

\[ \log(\phi[M_\odot]) [\text{Mpc}^{-3} \text{mag}^{-1}] \]

\[ z = 1.63 \]
QLF Comparison

2QZ break too strong
SDSS not deep enough
Small area surveys get luminous and high-z parts wrong.
Optical and X-ray alone may not fully describe the QLF, but combined, they do (at least the answers are consistent).

Hopkins, Richards, & Hernquist 2007
HRH07
L-dependence of Clustering as a Diagnostic Test

Myers et al. 2007a
z-dependence of Clustering
With a large enough sample, can break $L$-$z$ degeneracy.

$L$-dependence of bias is a discriminator of feedback models.

Traditional models: $b = f(L)$.
Hopkins et al: $b \neq f(L)$
Ideally? SDSS+UKIDSS+Spitzer

Current wide-field Spitzer limits are quite complimentary with SDSS limits (UKIDSS too). Just need more area (~1000 sq. deg.)
ADIOS (The Advanced Deep Infrared/Optical Spitzer Survey)

Combine SDSS and Spitzer in the SDSS Southern Equatorial Stripe region where the SDSS has >30 epochs of data over 8 years and the co-added depth is $g \sim 24.5$
Summary

What we know:
- QLF roughly a double power-law
- Slopes (bright and faint) appear to evolve (feedback constraint?)
- Decreasing mass scale with cosmic time (cosmic downsizing)
- Obscuration L-dependent ($\sim 4:1$ at $L_X=10^{42}$, $\sim 1:1$ at $L_X=10^{44}$)

What we want to know:
- Is bright end slope evolution real?
- Is bias independent of luminosity?
- Obscured fraction as $f(L,z)$
- $L/L_{Edd}$ dependence

How to get there: Push wide optical surveys deeper
- Very wide IR surveys
Summary

What we know:
QLF roughly a double power-law
Slopes (bright and faint) appear to evolve (feedback constraint?)
Decreasing mass scale with cosmic time (cosmic downsizing)
Obscuration L-dependent (≈4:1 at \( L_X=10^{42} \), ≈1:1 at \( L_X=10^{44} \))

What we want to know:
Is bright end slope evolution real?
Is bias independent of luminosity?
Obscured fraction as \( f(L,z) \)
\( L/L_{\text{Edd}} \) dependence

How to get there: Push wide optical surveys deeper
Very wide IR surveys
The Dominant Feedback Mechanism

• Not radio jets!
• Possibly accretion disk winds
• Note that *ALL* quasars have accretion disk winds (not just BALs) -- by definition
The Future: Efficient Target Selection + Photo-z’s

Current selection techniques for quasars are inefficient in the optical (~50-80% success rate).

It takes MUCH longer to take spectra than to get photometry.

More efficient (~95%) selection algorithms coupled with accurate photometric redshift techniques can make spectroscopy obsolete.
Traditional Quasar Selection

![Quasar Selection Diagram]

- z < 2.2 quasars
- z > 3 quasars
Kernel Density Estimation
Dual-tree Method

- Tree building is $O(N \log N)$; usually fast in comparison to the rest of computation
- Classification of 500k objects in ~900 sec for reasonable bandwidths
Comparing Probability Densities

100,000 $z < 3$ quasars in DR1 (95% efficient to $g = 21$)

SDSS is 85% efficient to $g = 19$

Potential for 1,000,000 quasars from $0 < z < 5$ in the whole SDSS area.

Richards et al. 2004c
Separating Quasars from Stars
Photometric redshifts are 80% accurate to within 0.3.

Weinstein, Richards et al. 2004
DR5 Catalog Update

Extension to $z>3$

Of order 1 million quasars

Working on improving efficiency
<table>
<thead>
<tr>
<th>Survey</th>
<th>Number</th>
<th>MagLim</th>
<th>Area</th>
<th>Z Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG</td>
<td>~100</td>
<td>B=16.2</td>
<td>10,700</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Osmer80</td>
<td>~100</td>
<td>V~19</td>
<td>340</td>
<td>&gt;1.8</td>
</tr>
<tr>
<td>LBQS</td>
<td>~1000</td>
<td>B=18.5</td>
<td>600</td>
<td>[0,3.4]</td>
</tr>
<tr>
<td>2QZ</td>
<td>~25,000</td>
<td>B=20.85</td>
<td>650</td>
<td>[0,3]</td>
</tr>
<tr>
<td>SDSS</td>
<td>~70,000</td>
<td>i=19.1</td>
<td>8000</td>
<td>[0,5.4]</td>
</tr>
<tr>
<td>Fan high-z</td>
<td>~50</td>
<td>z=20</td>
<td>5000</td>
<td>[3.5,6.4]</td>
</tr>
<tr>
<td>SDSSphoto</td>
<td>~1 million</td>
<td>i=21</td>
<td>8000</td>
<td>[0,5]</td>
</tr>
<tr>
<td>Jiang et al. 2006</td>
<td>~400</td>
<td>G=22.5</td>
<td>3.9</td>
<td>[0,5]</td>
</tr>
<tr>
<td>COMBO-17</td>
<td>~100</td>
<td>R=23</td>
<td>0.25</td>
<td>[1,5]</td>
</tr>
<tr>
<td>Ueda et al. 2003</td>
<td>~250</td>
<td>Varies</td>
<td>Varies</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Barger et al. 2005</td>
<td>~600</td>
<td>Varies</td>
<td>Varies</td>
<td>[0,5]</td>
</tr>
<tr>
<td>Hasinger et al. ‘05</td>
<td>~2500</td>
<td>Varies</td>
<td>Varies</td>
<td>[0,5]</td>
</tr>
<tr>
<td>Brown et al. 2006</td>
<td>183</td>
<td>1 mJy</td>
<td>7</td>
<td>[1,5]</td>
</tr>
<tr>
<td>Wall et al. 2005</td>
<td>~300</td>
<td>0.25 Jy</td>
<td>10000?</td>
<td>[0,4]</td>
</tr>
</tbody>
</table>
Hopkins et al. 2005

Others: assume quasar is either “on” or “off” and that there is a mass/luminosity hierarchy.

Hopkins et al.: quasar phase is episodic and “all quasars are created equal” (with regard to mass/luminosity).
Current wide-field Spitzer limits are quite complimentary with SDSS limits (UKIDSS too). Just need more area (~1000 sq. deg.)
Quasar Spectral Energy Distribution

Richards et al. 2006
Modern Quasar SEDs

Richards et al. 2006
Quasar Luminosity Function

Typically fit by double power-law

Space density of quasars as a function of redshift and luminosity
Recent Progress: SDSS+2dF

A ~100 sq. deg. Survey of quasars identified with the 2dF spectrograph from SDSS imaging.

Faint quasars are more numerous than previously thought.

Richards et al. (2005)
Dynamic Range

The diagnostic power of the QLF is dependent on the dynamic range of the sample. One wants the largest possible redshift and luminosity range over the largest possible area of sky.

Hasinger et al. 2005