Supermassive Black Holes in Active Galactic Nuclei

Bradley M. Peterson
The Ohio State University

UFRGS Lectures
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Topics to be Covered

• **Lecture 1:** AGN properties and taxonomy, fundamental physics of AGNs, AGN structure

• **Lecture 2:** The broad-line region, emission-line variability, reverberation mapping principles, practice, and results, the radius–luminosity relationship, AGN outflows and disk-wind models

• **Lecture 3:** AGN luminosity function and its evolution, role of black holes, direct/indirect measurement of AGN black hole masses, relationships between BH mass and AGN/host properties, “industrial scale” reverberation mapping
Cosmic Evolution of AGNs

- Very luminous AGNs were much more common in the past.
- The “quasar era” occurred when the Universe was 10-20% its current age.
Modern Surveys

- Recent surveys are detecting luminous AGNs at very high redshift and large numbers of quasars at intermediate redshift.

SDSS quasars with $z > 5.7$
Fan 2006
Largest Known Redshifts
High-z Quasars

• Current highest quasar redshift $z \approx 7.1$
  – Supermassive black holes appeared within a few hundred million years of the Big Bang
  – Metals in their spectra indicate processing in stars already occurred.
Evolution of the QSO Luminosity Function

- **Density evolution:** quasars “turn off” and luminosity function translates downward.
- Several problems, most importantly that local density of very luminous quasars is overpredicted.
Evolution of the QSO Luminosity Function

- **Luminosity evolution:** quasars just become fainter with time.
- Does not agree with observation that most quasars are emitting near the Eddington limit: the typical nearby quasar is about 50 times fainter than it would have been at \( z \approx 2 \).

\[
\phi ( \Delta M, z ) = \frac{\text{number of AGNs}}{(\text{mag}^{-1} \text{Gpc}^{-3})}
\]

Luminosity evolution
Evolution of the AGN Luminosity Function

• Because we can now observe lower-luminosity AGNs at high-z, our view of evolution of the luminosity function has changed in the last decade.

• Preferred scenario is now “luminosity-dependent density evolution” (LDDE) or “cosmic downsizing.”

Comoving density of 2dF+SDSS quasars at different luminosities. Croom et al. 2009
Cosmic Downsizing

- The space density of lower-luminosity AGNs peaks later in time than that of luminous AGNs.
Evolution of the AGN Luminosity Function

• Luminosity-dependent density evolution is most clearly seen in the X-rays
  − Low-luminosity systems are accessible at high $z$ in X-rays

X-ray luminosity function
Brandt & Hasinger 2005
Supermassive Black Holes Are Common

• Supermassive black holes are found in galaxies with large central bulge components.
• These are almost certainly remnant black holes from the quasar era.
• To understand accretion history, we need to determine black-hole demographics.

M 87, a giant elliptical SMBH $> 3\times10^9 \, M_\odot$
Relationship Between Black Hole Mass and Host Galaxy Properties

- Remarkable since BH constitutes 0.5% of the mass of the bulge.
- Indicates a close (evolutionary?) relationship between BH growth/bulge formation?
  - Do these evolve over time?
- Do supermassive black holes affect their host galaxies?

$M_{\text{BH}} - \sigma_*$ relationship

$M_{\text{BH}} - L_{\text{bulge}}$ relationship

Marconi & Hunt 2004
A Current Paradigm: Feeding and Feedback

• Supermassive black holes are “active” if there is a large reservoir of gas to “feed” them.
  – Quasars were more common in the past because less gas was locked up in stars; galaxies were gas rich.

• Once a quasar reaches a high-enough luminosity, energetic “feedback” (radiation, winds, jets) from quasars (and massive stars?) heats or removes the ISM, shutting down star formation.
  – There is thus a close correlation between black hole mass and galaxy mass.
Role of Quasars in Galaxy Formation
(or why galaxy formation theorists suddenly like quasars…)

• Models of galaxy formation predict that massive galaxies should still have large reservoirs of gas and active star formation.

• Feedback from accretion onto supermassive black holes might provide the energy necessary to regulate cooling and subsequent star formation.
Does This Represent an Evolutionary Sequence?

Mass $\rightarrow$ Age $\rightarrow$

$u-r$ colour

Velocity dispersion $\sigma$ [kms$^{-1}$]

Orange dots: Quiescent early-type galaxies
Gray dots: Non-early type galaxies

Schawinski et al. 2007
Evolution of the $M_{\text{BH}} - \sigma^*$ and $M_{\text{BH}} - L_{\text{bulge}}$ Relationships

• Some claims for evolution of the $M_{\text{BH}} - \sigma^*$, $M_{\text{BH}} - L_{\text{bulge}}$ relationships, other claims for no evolution, or even no causal relation.

• To test this, we must use (indirect) scaling methods for strong UV emission lines for luminous and distant quasars.
  – One direct (dubious) black hole mass measurement at $z = 2.17$ (Kaspi et al. 2007). No others at $z > 0.3$. 
Measuring Central Black-Hole Masses

• Virial mass measurements based on motions of stars and gas in nucleus.
  – Stars
    • Advantage: gravitational forces only
    • Disadvantage: requires high spatial resolution
      – larger distance from nucleus ⇒ less critical test
  – Gas
    • Advantage: can be observed very close to nucleus, high spatial resolution not necessarily required
    • Disadvantage: possible role of non-gravitational forces (radiation pressure)
Virial Estimators

<table>
<thead>
<tr>
<th>Source</th>
<th>Distance from central source</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Ray Fe Kα</td>
<td>3-10 $R_S$</td>
</tr>
<tr>
<td>Broad-Line Region</td>
<td>200–10$^4$ $R_S$</td>
</tr>
<tr>
<td>Megamasers</td>
<td>$4 \times 10^4$ $R_S$</td>
</tr>
<tr>
<td>Gas Dynamics</td>
<td>$8 \times 10^5$ $R_S$</td>
</tr>
<tr>
<td>Stellar Dynamics</td>
<td>$10^6$ $R_S$</td>
</tr>
</tbody>
</table>

In units of the Schwarzschild radius $R_S = 2GM/c^2 = 3 \times 10^{13} M_8$ cm.

Mass estimates from the virial theorem:

$$M = f \left( r \frac{\Delta V^2}{G} \right)$$

where
- $r$ = scale length of region
- $\Delta V$ = velocity dispersion
- $f$ = a factor of order unity, depends on details of geometry and kinematics
Direct vs. Indirect Methods

• *Direct methods* are based on dynamics of stars or gas accelerated by the central black hole.
  – Stellar dynamics, gas dynamics, reverberation mapping

• *Indirect methods* are based on observables correlated with the mass of the central black hole.
  – $M_{\text{BH}}-\sigma^*$ and $M_{\text{BH}}-L_{\text{bulge}}$ relationships, fundamental plane, AGN scaling relationships ($R_{\text{BLR}}-L$)
“Primary”, “Secondary”, and “Tertiary” Methods

- Depends on model-dependent assumptions required.
- Fewer assumptions, little model dependence:
  - Proper motions/radial velocities of stars and megamasers (Sgr A*, NGC 4258+)
- More assumptions, more model dependence:
  - Stellar dynamics, gas dynamics, reverberation mapping
    - Since the reverberation mass scale currently depends on other “primary direct” methods for a zero point, it is technically a “secondary method” though it is a “direct method.”
Reverberation Mapping Results

- Reverberation lags have been measured for ~50 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification
  - Highest ionization lines are also broadest!
A Virialized BLR

- $\Delta V \propto R^{-1/2}$ for every AGN in which it is testable.
- Suggests that gravity is the principal dynamical force in the BLR.
  - Caveat: radiation pressure!
Reverberation-Based Masses

\[ M_{\text{BH}} = f \left( r \Delta V^2 / G \right) \]

Observables:
\( r = \text{BLR radius (reverberation)} \)
\( \Delta V = \text{Emission-line width} \)

“Virial Product” (units of mass)

Set by geometry and inclination
(subsumes everything we don’t know)

If we have independent measures of \( M_{\text{BH}} \), we can compute an ensemble average \( <f> \)
Measuring the Emission-Line Widths

• We preferentially measure line widths in the rms residual spectrum.
  – Constant features disappear, less blending.
  – Captures the velocity dispersion of the gas that is responding to continuum variations.

AGN $M_{\text{BH}} - \sigma_*$ Relationship

- Assume zero point of most recent quiescent galaxy calibration.
  $\langle f \rangle = 4.19 \pm 1.08$

- Maximum likelihood places an upper limit on intrinsic scatter
  $\Delta \log M_{\text{BH}} \sim 0.40$ dex.
  - Consistent with quiescent galaxies.

The AGN $M_{\text{BH}}-L_{\text{bulge}}$ Relationship

- Line shows best-fit to quiescent galaxies
- Maximum likelihood gives upper limit to intrinsic scatter $\Delta \log M_{\text{BH}} \sim 0.17$ dex.
  - Smaller than quiescent galaxies ($\Delta \log M_{\text{BH}} \sim 0.38$ dex).
Black Hole Mass Measurements
(units of $10^6 \, M_\odot$)

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>NGC 4258</th>
<th>NGC 3227</th>
<th>NGC 4151</th>
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<tr>
<td>Direct methods:</td>
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<tr>
<td>Megamasers</td>
<td>38.2 ± 0.1</td>
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<td>Stellar dynamics</td>
<td>33 ± 2</td>
<td>7–20</td>
<td>47$^{+11}_{-14}$†</td>
</tr>
<tr>
<td>Gas dynamics</td>
<td>25 – 260</td>
<td>20$^{+10}_{-4}$</td>
<td>30$^{+7.5}_{-22}$</td>
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<td>Reverberation</td>
<td>N/A</td>
<td>7.63 ± 1.7</td>
<td>46 ± 5</td>
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Quoted uncertainties are statistical only, not systematic.

References: see Peterson (2010) [arXiv:1001.3675]
† Onken et al., in preparation
Reverberation-Based Masses

- Combine size of BLR with line width to get the enclosed mass:
  \[ M_{BH} = f \left( r \, \Delta V^2 / G \right) \]
- Without knowledge of the BLR kinematics and geometry, it is not possible to compute the mass accurately or to assess how large the systematic errors might be.
  - Low-inclination thin disk \((f \propto 1/\sin^2 i)\) could have a huge projection correction.
Plausible BLR Geometry

- Unified models suggest that Type 1 AGNs are observed at inclinations $0^\circ \leq i \leq \sim 45^\circ$.
  - Lags are unaffected if axial symmetry and isotropic line emission
  - Line widths can be severely affected by inclination.
    - A “generalized thick disk” parameterization:
      $$ f \propto \frac{1}{(a^2 + \sin^2 i)} $$
      Collin et al. (2006)
Evidence Inclination Matters

• Relationship between $R$ (core/lobe) and FWHM.
  – Core-dominant are more face-on so lines are narrower.
    Wills & Browne 1986

• Correlation between $\alpha_{\text{radio}}$ and FWHM
  – Flat spectrum sources are closer to face-on and have smaller line widths
    • $\alpha_{\text{radio}} > 0.5$: Mean FWHM = 6464 km s$^{-1}$
    • $\alpha_{\text{radio}} < 0.5$: Mean FWHM = 4990 km s$^{-1}$
  – Width distribution for radio-quiets like flat spectrum sources (i.e., closer to face-on)
    Jarvis & McLure 2006
Stellar and gas dynamics requires resolving the black hole radius of influence $r_*$. 

$r_* = \frac{GM_{\text{BH}}}{\sigma_*^2}$

- **Quiescent galaxies** (stellar, gas dynamics, megamasers)
- **Reverberation AGNs**
Masses of Black Holes in Quasars

• Stellar and gas dynamics requires higher angular resolution to proceed further.
  – Even a 30-m telescope will not vastly expand the number of AGNs with a resolvable $r_*$.

• Reverberation is the future path for direct AGN black hole masses.
  – Trade time resolution for angular resolution.
  – Downside: resource intensive.

To significantly increase number of measured masses, we need to go to secondary methods.
The $R-L$ Relation

- Empirical slope $\sim 0.55 \pm 0.03$
- For H$\beta$ over the calibrated range ($42 \leq \log \lambda L_{5100}$ (ergs s$^{-1}$) $\leq 46$ at $z \approx 0$), $R-L$ is nearly as effective as reverberation.

Bentz+ 2013
Measuring the Emission-Line Widths

- Trickier in “mean” or “single-epoch” spectra because of blending.
- Another important issue is how to characterize the line width:
  - FWHM?
  - Line dispersion?

Characterizing Line Widths

**FWHM:**
- Trivial to measure
- Less sensitive to blending and extended wings

**Line dispersion \( \sigma_{\text{line}}: \)**
- Well defined
- Less sensitive to narrow-line components
- More accurate for low-contrast lines

\[
\sigma_{\text{line}} = \left( \frac{\lambda^2}{\langle \lambda^2 \rangle} - \lambda_0^2 \right) = \left( \frac{\int \lambda^2 P_{\lambda} d\lambda}{\int P_{\lambda} d\lambda} \right) - \lambda_0^2
\]
Hβ Profiles in NLS1s Have Low Values of FWHM/$\sigma_{\text{line}}$

- This matters because their black hole masses depend on the line width measure (squared!).
- Systematically shifts NLS1s away from other AGN masses.
Incorrect Choice Introduces Bias Based on Line Width

- The importance of this is that the masses are shifted *systematically*
  - In this case, the high-Eddington rate objects have smaller masses for FWHM than for $\sigma_{\text{line}}$
- Leads to incorrect BH mass function and other troubles...
The Sub-Eddington Limit

- The most massive black holes seem to be unable to approach the Eddington limit.  
  Steinhardt & Elvis 2010
- Line widths used were from Gaussian fits to broad emission lines.  
  Shen, Greene, et al. 2008

Steinhardt & Elvis 2010
The sub-Eddington limit vanishes when the masses are based on $\sigma_{\text{line}}$ measured directly from the spectra instead of FWHM from a Gaussian fit.
Direct Observational Test: Mass Must Be Constant

- Only NGC 5548 has much dynamic range
  - $\sigma_{\text{line}}$ is slightly favored, but only slightly
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Cosmological Applications

- Because the $R-L$ relationship has so little scatter, cosmological applications are possible.
- $R \Rightarrow L \Rightarrow D_L$

Watson, Denney, Vestergaard, & Davis 2011
Reverberation Mapping Goals

- Determine geometry and kinematics of BLR
- Determine black hole masses
- Calibrate scaling relationships for indirect black hole mass estimates
- Determine/confirm cosmological parameters
Reverberation Mapping Goals

- Geometry and kinematics of BLR
  - Velocity-resolved RM (expensive!)

- Black hole masses
  - High accuracy (~50% or better)
    - Velocity-resolved RM (expensive!)
  - Moderate accuracy (factor of ~3–5)
    - Mean lag measurement (moderately expensive)
    - High S/N single spectra + scaling relationships (somewhat expensive)
  - Low accuracy (order of magnitude)
    - Survey-quality single spectra + scaling relationships (inexpensive. But you get what you pay for)
Reverberation Mapping Goals

• Calibrate scaling relationships for indirect black hole mass estimates
  – $H\beta \, R-L$ well-characterized with intrinsic scatter $\sim 0.13$ dex
  – Still somewhat of an open issue for other lines
    • Or is it?
Independent confirmation of $R-L$ from microlensing, including high-ionization lines.

Guerras, Kochanek + 2012
Reverberation Mapping Goals

• Calibrate scaling relationships for indirect black hole mass estimates
• Cosmological applications

These require measurement of BLR size, preferably in a large number of sources. Are there less expensive ways to do this?
Sparse Sampling

- If you have a good continuum light curve, you can get by with more sparsely sampled line light curves
  - Especially if you use multiple lines with different lags

Barth+ 2011
“Stacked Spectra” or Extremely Sparse Sampling

- A minimal number of line measurements can be probabilistically matched to a particular lag with good continuum sampling.
  - Can be done with as few as two spectra, though fidelity low.

Fine+ 2013
Photometric Reverberation

• The Great Hope:
  – If we can get emission-line lags from ground-based broad-band data, we can get thousands of BLR radii and black hole masses efficiently.
  – With surveys like Pan-STARRS and LSST, we can get the monitoring data essentially for free.
    • R-L for cosmology for free!
    • Add one (high-quality) spectrum per target to get masses.
Photometric Reverberation

• The Great Challenge:
  – The line flux is typically a small part of the total waveband flux.
  – Line flux variations are relatively small.

\[
\frac{\Delta F}{F} = \frac{E W_{\text{line}}}{F W H M_{\text{filter}}} \times F_{\text{var}}
\]

Estimating these quantities for H$\beta$ in Johnson $B$-band:

\[
\frac{\Delta F}{F} \approx \left( \frac{60 \, \text{Å}}{940 \, \text{Å}} \right) \times (0.10 \pm 0.06) = 0.006 \pm 0.004
\]

Typical photometric errors are $\sigma/F \sim 0.01$
Photometric Reverberation

• Approaches:

\[
\frac{\Delta F}{F} \approx \frac{EW_{\text{line}}}{FWHM_{\text{filter}}} \times F_{\text{var}} \gg \sigma/F
\]

Stronger line, e.g., H\(_\alpha\)

Narrower filter

Reduce photometric errors

Caution: As with spectroscopic reverberation, time sampling and duration remain important issues.
**R-L Relationship for Mg II $\lambda 2798$**

- Little reverberation data on Mg II $\lambda 2798$
  - Existing lag data ambiguous, particularly those that are contemporaneous with Balmer lines.
  - Relies on assumption that Mg II arises co-spatially with Balmer lines.

*Metzroth, Onken, & Peterson (2006)*
**R-L Relationship for Mg II λ2798**

- From SDSS spectra, Shen et al. (2008) find

\[
\log \left[ \frac{\text{FWHM}(H\beta)}{\text{FWHM}(\text{Mg II})} \right] = 0.0062 \text{ dex}
\]

with scatter ~0.11 dex.

---

McLure & Jarvis (2002)

McGill et al. (2008)

Shen et al. (2008)
$R-L$ Relationship for Mg II $\lambda 2798$

- Onken & Kollmeier find that the line width ratio has dependence on Eddington ratio and is correctable.

Onken & Kollmeier 2008
**R-L Relationship for C IV λ1549**

- First used by Vestergaard (2002) to estimate BH masses at high-\(z\).
- **Pros:**
  - Limited data suggest same R-L slope as Hβ (despite Baldwin Effect).
  - Consistent with virial relationship, at least in low-luminosity AGNs.
- **Cons:**
  - Often strong absorption, usually in blue wing.
  - Extended bases (outflows), especially in NLS1s.

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![Graph showing R-L relationship for C IV λ1549](image)
Other Scaling Relationships

- The width of the narrow [O \textsc{iii}] $\lambda 5007$ line can be used as a surrogate for the stellar velocity dispersion.
- Intrinsic scatter: 0.10 – 0.15 dex.

Bonning et al. 2005, Gaskell 2009

Bonning et al. 2005

Greene & Ho 2005
Other Scaling Relationships

- There are other luminosity indicators that can be used as proxies for $R_{\text{BLR}}$:
  - 2-10 keV flux. Scatter: 0.26 dex
  - Flux Hβ broad component. Scatter: 0.22 dex.
  - Flux [O III] $\lambda$5007. Scatter: 0.29 dex.
  - Flux [O IV] $\lambda$25.8μm. Scatter: 0.35 dex.

- These are useful when uncontaminated continuum is difficult or impossible to measure.

Greene et al. 2010
Measurement of Central Black Hole Masses: The Mass Ladder

Phenomenon:
- Quiescent Galaxies
- Type 2 AGNs
- Type 1 AGNs

Direct Methods:
- Stellar, gas dynamics
- Megamasers
- 1-dRM
- 2-dRM

Fundamental Empirical Relationships:
- $M_{BH} - \sigma_*$

Indirect Methods:
- Fundamental plane:
  - $\Sigma_e, r_e \Rightarrow \sigma_* \Rightarrow M_{BH}$
- [O III] line width
  - $\Delta V \Rightarrow \sigma_* \Rightarrow M_{BH}$
- Broad-line width $\Delta V$ & size scaling with luminosity
  - $R \propto L^{1/2} \Rightarrow M_{BH}$

Application:
- BL Lac objects
- Low-z AGNs
- High-z AGNs
Scaling Relationships: Use with Caution

• When you think you’re measuring mass, you’re really measuring

\[ M_{\text{BH}} \propto R(\Delta V^2) \propto L^{1/2}(\Delta V^2) \]

• When you think you’re measuring Eddington ratio, you’re really measuring

\[ \frac{L}{L_{\text{Edd}}} \propto \frac{L}{M_{\text{BH}}} \propto \frac{L}{L^{1/2}(\Delta V^2)} \propto \frac{L^{1/2}}{\Delta V^2} \]
Summary of Key Points

• Direct methods of mass measurement:
  – Most dynamical methods are limited by angular resolution to nearest tens of Mpc.
  – Reverberation mapping is effective even at large distances, but currently limited by systematics and dependence on other methods for calibration.

• Indirect methods:
  – Can be used for large samples, but less reliable for individual sources.