Inflow and Outflow in the Broad Line Region of AGN

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Lick AGN Monitoring Project (LAMP) 2008, 2011, and 2016 reverberation mapping campaigns

OSU 2010, 2014 reverberation mapping collaboration

AGN STORM collaboration

LCO AGN Key Project collaboration
Measuring black hole masses in AGN

Broad line region

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Credit: NASA/CXC/M.Weiss
Measuring black hole masses in AGN

Substitute *time resolution* for spatial resolution

Resolve motions of broad line region gas around the black hole
Reverberation mapping

Blandford & McKee 1982
Peterson 1993
Peterson et al. 2004
Peterson 2014
And Bentz et al. 2015 for the AGN Black Hole Mass Database

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Reverberation mapping

Accretion disk

Broad line region gas

Blandford & McKee 1982
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Credit: NASA/CXC/M.Weiss
Reverberation mapping

Ionizing photons to the observer

Broad line region gas

Accretion disk

Continuum emission from accretion disk

Flux vs. Time

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Reverberation mapping

Ionizing photons to broad line region gas

Broad line region gas

Accretion disk

Ionizing photons to the observer

Continuum emission from accretion disk

Flux vs. Time

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Reverberation mapping

Ionizing photons to the observer

Broad line region gas

Accretion disk

Ionizing photons to the observer

Continuum emission from accretion disk

Broad line flux

Time

Flux

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Reverberation mapping black hole masses

- Broad emission line profile
- Continuum emission from accretion disk
- Broad line flux
- Flux vs. Wavelength
- Flux vs. Time
- V
- τ
Reverberation mapping black hole masses

\[ M_{\text{vir}} = f \, \nu^2 \, c \, \tau / G \]
Reverberation mapping black hole masses

\[ M_{\text{vir}} = \left( f \right) v^2 c \frac{\tau}{G} \]
Reverberation mapping black hole masses

\[ M_{\text{vir}} = f \nu^2 c \tau / G \]
Reverberation mapping black hole masses

\[ M_{\text{vir}} = f \nu^2 c \tau / G \]

Determining \( f \) is our biggest challenge!
Reverberation mapping black hole masses

\[ M_{\text{vir}} = f v^2 c \tau / G \]

Determining \( f \) is our biggest challenge!

- Shell
- Disk
- Ring

Woo et al. 2013

Gives us an average \( f \)...

and adds uncertainty of \(~0.4\) dex (x2.5)

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Measuring $M_{\text{BH}}$ at higher $z$

Allows for single-epoch AGN black hole mass estimates:
- Use line width to get $v$
- Use $L_{\text{AGN}}$ to get $r_{\text{BLR}}$

Apply to any AGN with a broad emission line spectrum

→ large source of uncertainty is unknown structure and evolution of the BLR

BLR radius – AGN luminosity relation from Bentz et al. 2013

$\alpha = 0.546^{+0.027}_{-0.028}$
$\sigma = 0.13^{+0.02}_{-0.02}$ dex
How can we measure the properties of the broad line region?

- Quantitatively constrain the structure of the broad line region
- Measure $f$ for individual AGN
- Measure the black hole mass with $<0.4$ dex uncertainty

Model reverberation mapping data using a model for the broad line region
A simply parameterized phenomenological model for the broad line region

1. Model the AGN continuum light curve using Gaussian processes to evaluate the continuum flux at arbitrary times.

2. Model the geometry and dynamics of the broad line region in order to assign positions and velocities to the point particles.

3. Make model broad emission line profiles to compare with the data.
A simply parameterized phenomenological model for the broad line region

- **Geometry**
  
  ![Diagram of geometry showing a transition from a transparent to opaque mid-plane, and a shift from a disk to a cone with more emission from near or far side.]

- **Dynamics**
  
  ![Diagram of dynamics showing near-circular, inflowing, and outflowing configurations around a black hole (BH).]
What is the structure of the Hβ-emitting broad line region?
Inferred broad line region geometry

The Lick AGN Monitoring Project (LAMP) 2008 results
(Pancoast, Brewer, Treu et al. 2014)

- H\(\beta\)-emitting geometry: close to face-on thick disks
- Consistent with preferential emission back towards central ionizing source
- Dynamics: inflow and/or elliptical orbits
- Black hole mass constrained with 0.15 – 0.3 dex uncertainty

Spectral decomposition from: Park et al. 2012a

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Higher black hole mass, redshift, and AGN luminosity

Dynamics mostly inflow

3C 120 has a measured radio jet inclination angle $\sim 16$ deg (Agudo+12)


The OSU 2010 reverberation mapping results
The OSU 2014 reverberation mapping preliminary results

- 2+ AGNs with data quality sufficient for BLR modeling
- NGC 2617 is a “changing-look” AGN and new reverberation mapping target

Data from: Fausnaugh et al. 2017b

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The Lick AGN Monitoring Project 2011

- Campaign designed with BLR modeling in mind
- First 4 AGN with preference for outflowing dynamics
- Second dataset for Arp 151

Data from: Barth et al. 2015

(Williams, Pancoast et al. in preparation)
What is the *structure* of the Hβ-emitting broad line region?

- **Geometry:** close to face-on thick disk, preferential emission back towards ionizing source, partly opaque disk mid-plane
- **Dynamics:** a range of near-circular elliptical orbits, inflow, and outflow

![Graph showing different emission scenarios](Image)

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How *robust* are these constraints?

Data from:
Bentz et al. 2009 (LAMP 2008)
Barth et al. 2015 (LAMP 2011)
Valenti et al. 2015 (LCO AGN Key Project 2015)
How robust are these constraints?

Data from:
Bentz et al. 2009 (LAMP 2008)
Barth et al. 2015 (LAMP 2011)
Valenti et al. 2015 (LCO AGN Key Project 2015)

Evolution in the BLR?

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(Pancoast et al. in preparation)
What about the big picture?
An average value of the $f$ factor

Using the full posterior PDFs for black hole mass for LAMP 2008, 2011, and the OSU 2010 datasets

$$\langle \log_{10}(f) \rangle = 0.56 \pm 0.08$$
$$\sigma(\log_{10}(f)) = 0.18 \pm 0.10$$

(Williams, Pancoast et al. in preparation)
Dependence of $f$ on AGN/BLR properties

The $f$ factor is most strongly correlated with inclination angle and opening angle of the disk

(Williams, Pancoast et al. in preparation)
Where do we go from here?
The new generation of reverberation mapping experiments

The AGN Space Telescope and Optical Reverberation Mapping Program (AGN STORM)

Monitored NGC 5548 using HST + optical ground-based telescopes covering Ly\(\alpha\), CIV, and H\(\beta\) simultaneously

\[ \tau = \alpha \left( \frac{\lambda}{\lambda_0} \right)^\beta - 1 \]

From Fausnaugh et al. 2016

Reverberation mapping of the AGN continuum:

- The accretion disk is larger than anticipated
- There is a measurable time lag between the UV and optical
- Inner broad line region overlaps with accretion disk

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The new generation of reverberation mapping experiments

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The Las Cumbres Observatory (LCO) AGN Key Project

Fully robotic monitoring of low-z AGNs, follow-up to explore evolution in the broad line region

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The new generation of reverberation mapping experiments

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The Lick AGN Monitoring Project 2016

Monitoring ~20 AGNs with higher luminosities, larger masses, and bigger broad line regions.

How does broad line region structure scale with AGN luminosity? Do we find more outflows?

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Conclusions

- Broad line region modeling of reverberation mapping allows us to:
  - Measure AGN black hole masses more precisely (0.1 – 0.3 dex uncertainty vs. ~0.4 dex)
  - Make first measurements of $f$ for individual AGN
  - Constrain the detailed geometry and dynamics of the broad line region
- In progress: increasing the sample from 10 to 15+ AGN with broad line region modeling
- Flexible framework to test broad line region models (e.g. AGN outflow models, photoionization physics)