Revealing the Hidden Broad Line Region in AGN Using Reverberation Mapping

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+ LAMP 2008 collaboration

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Black holes in active galaxies

- No hard distance limit on measuring $M_{BH}$ in active galactic nuclei (AGN).
- Measure $M_{BH}$ by constraining properties of the gas orbiting around the black hole in the broad line region (BLR).

Credit: C.M. Urry and P. Padovani
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Reverberation mapping

Black hole

Accretion disk

Broad line region gas
Reverberation mapping

- Black hole
- Accretion disk
- Ionizing photons to the observer
- Broad line region gas

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Reverberation mapping

Ionizing photons to the observer

Ionizing photons to broad line region gas

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Ionizing photons to broad line region gas

Broad line flux to the observer

Ionizing photons to the observer

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Continuum emission from accretion disk

Broad line flux

$\tau$

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Reverberation mapping

- Velocity of gas from the width of the broad emission line.
Reverberation mapping

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- Radius of the gas by measuring time lag between continuum and broad line flux changes.

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Reverberation mapping

- Velocity of gas from the width of the broad emission line.
- Radius of the gas by measuring time lag between continuum and broad line flux changes.
- Black hole mass:

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

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Measuring the mean $f$ factor

The $M_{\text{BH}}-\sigma_*$ relation from Woo et al. 2013

$$\langle f \rangle = 5.9^{+2.1}_{-1.5}$$

$$\log_{10}\langle f \rangle = 0.77 \pm 0.13$$

Largest uncertainty in reverberation mapped masses is scatter in

$$\log_{10}(f) \sim 0.4 \text{ dex}$$
The dynamical modeling approach

- Model reverberation mapping data using a geometric and dynamical model for the broad line region:
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  - Constrain the geometry and dynamics of the broad line region
  - Measure $f$ for individual AGN
  - Measure the black hole mass with $<0.4$ dex uncertainty

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BLR geometry: Face-on ring
Model broad line light curve
Model light curve + data (blue points)

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BLR geometry: Shell
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BLR geometry: Face-on disk
Model broad line light curve
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A simple phenomenological model of 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

Details in:
- Pancoast, Brewer, & Treu 2011
- Brewer, Treu, Pancoast et al. 2011
- Pancoast, Brewer, Treu et al. 2012
- Pancoast, Brewer, & Treu 2014
- Pancoast, Brewer, Treu et al. 2014
AGN continuum light curve model

Examples of the continuum light curve model for LAMP 2008

Gaussian processes:
→ a good model for AGN variability on the timescales of reverberation mapping data
→ includes errors from interpolation
→ allows extrapolation beyond ends of light curve

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Broad line region model: geometry and dynamics

- Geometry model of broad line emission:
  - Radial profile of emission: Gamma distribution

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Pancoast, Brewer, & Treu 2014
Broad line region model: geometry and dynamics

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  - Additional asymmetry:
    - More emission from near/far side
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- Dynamics model:
  - Only consider gravity of black hole
  - Near circular, inflowing, and outflowing orbits
The Lick AGN Monitoring Project (LAMP) 2008

- 64 nights of spectroscopy
- Photometry from KAIT at Lick, Palomar 60", Tenagra II, & MAGNUM at Haleakala Obs.

Walsh et al. 2009
Bentz et al. 2009

Monitored 12 AGNs:
- 9 with measured time lags
- 5 with BLR modeling

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Broad line region modeling results: LAMP 2008

(Pancoast, Brewer, Treu et al. 2014)

- Hβ-emitting geometry: close to face-on thick disks
- Consistent with preferential emission from the far side of the broad line region
- Hβ-emitting dynamics: near-circular or inflowing orbits
- Black hole mass constrained to within 0.15 – 0.3 dex uncertainty
Detailed results: Arp 151

**Posterior probability distributions and parameter correlations**

- **Black hole mass** (measured to 0.15 dex uncertainty)
- **Inclination angle** (0 is face-on)
- **Opening angle** (90 deg is a sphere)

**Geometry:** thick disk with opaque midplane and more emission from the far side and faces of the disk

**Dynamics:** mostly bound inflow

**Model fit to the data**

- Integrated Hβ light curves
- Hβ emission line profiles

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The $r_{\text{BLR}} - L_{\text{AGN}}$ Relation

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

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 line spectrum

Recipes for single-epoch mass estimates vary by up to 0.4 dex

→ dominant source of uncertainty is unknown structure of the BLR

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Decreasing AGN black hole mass uncertainties: the $f$ factor

Measure a mean value of $f$ without the $M_{\text{BH}} - \sigma_*$ relation

Is $f$ correlated with any properties of the AGN or broad line region?

With 5 AGN from LAMP 2008, no correlation between $f$ and black hole mass or AGN luminosity

Mean value of $f$ is $0.68 \pm 0.4$ with a dispersion of $0.75 \pm 0.4$

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Conclusions

- Broad line region modeling of reverberation mapping allows us to:
  - Measure AGN black hole masses more precisely (0.15 – 0.3 dex uncertainty vs. ~0.4 dex)
  - First measurements of $f$ for individual AGN
  - Constraints on the detailed geometry and dynamics of the broad line region
  - Published results for 6 AGN (LAMP 2008/2011) with more in progress
  - Flexible framework to test broad line region models
Broad line region model: geometry and dynamics

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$M_{BH} - \sigma_*$ Relation

![Graph showing the $M_{BH} - \sigma_*$ Relation.](image)

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Transfer functions: Arp 151

MEMEcho results from Bentz et al. 2010

(20 Å ~ 1100 km/s)
Transfer functions: PG 2130+099

MEMECho results from Grier et al. 2013

(20 Å ~ 1100 km/s)
Transfer functions: Mrk 335

MEMEcho results from Grier et al. 2013

(20 Å ~ 1100 km/s)