Methods of Measuring Black Hole Masses: Reverberation Mapping

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Black Hole Masses in AGNs

Dynamical methods generally not feasible in AGNs
- AGNs rare = distant, poor spatial resolution
- AGNs are bright, outshine the “test particles”

Use variability instead → Reverberation mapping
- relies on time resolution instead of spatial resolution

\[ M_{BH} = f \frac{RV^2}{G} \]

- \( R \) – size of emission region
- \( V \) – velocity of gas in that region
- \( f \) – order unity scale factor

RM Assumptions:
1. \( R \) (continuum emission region) << \( R \) (BLR)
2. time delays arise from light travel time effects
3. optical continuum has simple relationship to ionizing continuum

RM does not assume any specific models
AGN Unified Model

- Narrow Line Region
- Broad Line Region
- Jet
- Black Hole
- Accretion Disk
- Obscuring Torus
AGN Unified Model

AGNs (Type 1)

Jet

Narrow Line Region

Broad Line Region

Black Hole

Accretion Disk

Obscuring Torus

Broad-line AGNs (Type 1)
AGN Unified Model

Narrow-line AGNs (Type 2)

Broad-line AGNs (Type 1)

Jet

Narrow Line Region

Broad Line Region

Black Hole

Accretion Disk

Obscuring Torus

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AGN Unified Model

Blazars

Narrow-line AGNs (Type 2)

Broad-line AGNs (Type 1)

Jet

Narrow Line Region

Broad Line Region

Accretion Disk

Black Hole

Obscuring Torus

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AGN Scales or Why It’s Hard to Study the BLR in Detail

Orbit of Sedna
aphelion = 928AU
= 5.4 light days

Radius of Seyfert BLR
~5 light days

Inner Solar System
AGN Scales or Why It’s Hard to Study the BLR in Detail

Orbit of Sedna
aphelion = 928AU
= 5.4 light days

Embedded in the center of a galaxy
~40Mpc away (z~0.01)
Measuring the BLR Radius -- RM Cartoon

Telescope

AGN

To observer

BH

0.01r/c

0.5r/c

r/c

1.5r/c

2r/c

Broad Line Region

Red = continuum

Purple = broad line

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Measuring the BLR Radius -- RM Cartoon

Telescope

AGN

$\tau = 0$

$\tau = r/c$

$\tau = 2r/c$

Average $= \tau = r/c$

Red = continuum

Purple = broad line

To observer

0.01$r/c$

0.5$r/c$

1.5$r/c$

2$r/c$

BH

Broad Line Region
Example Data – NGC 4151

Cross-correlation → time delay of broad line response to continuum variations

Time delay ($c\tau$) \(\rightarrow\) average BLR radius $R$
measured for \(~50\) AGNs

width of variable line emission \(\rightarrow\)
line-of-sight BLR gas velocity ($V$)

\[ M_{BH} = f \frac{RV^2}{G} \]

$f$ includes BLR physical details
(e.g., inclination, geometry, kinematics)
The Fudge Factor $f$

Assume $M_{BH} - \sigma$ relationship is same for AGNs and quiescent galaxies

population average:

$$<f> = 5.2 \pm 1.1$$

$\sigma$ difficult to measure for high-L AGNs ($z > 0.1$)

Morphological biases in $\sigma$ measurements?

Woo et al. 2010
Virial Behavior in the BLR

\[ V \propto T^{-1/2} \]

where measurements exist for multiple emission lines

**Peterson & Wandel 2002**

**Kollatschny 2003**

**Bentz et al. 2010**
Consistency with Dynamical Masses

Stellar and gas dynamical measurements for 2 AGNs with RM masses

Dynamical and RM masses are generally consistent for NGC 4151 and NGC 3227

More direct comparisons are needed, limited by AGN distances

Davies et al. 2006, Onken et al. 2007, Hicks & Malkan 2008
Bayesian Modeling of RM Data

Fits RM datasets with plausible BLR models

Simple RM:
\[ \log M_{\text{BH}} = 6.82 \pm 0.07 \]
(Bentz et al. 2009)

vs.

Bayesian modeling:
\[ \log M_{\text{BH}} = 6.51 \pm 0.28 \]
(Brewer et al. 2011)

Models are still simplistic

Need to study more objects

\( i = 90 \) defined as face-on

Brewer et al. 2011
Echo Mapping - BLR Transfer Function

\[ \Delta L(v,t) = \int_0^\infty \Psi(v,\tau) \Delta C(t-\tau) d\tau \]

recovered transfer function rules
out outflow

possible evidence for inflow

Bentz et al. 2010

(a) rotation
(b) inflow
(c) outflow
M-L relationship

AGN $L_{\text{bulge}}$ from 2-D decomposition of optical HST images

AGN M-L relationship and M-L relationship for only early type quiescent galaxies are consistent

Needs to be studied in NIR to minimize dust

*Bentz et al. 2011, in prep*
Single Epoch $M_{BH}$ Estimates

\[ M_{BH} = f \frac{RV^2}{G} \]

$R - L$ relationship yields black hole mass with one spectrum and two measurements:
Single Epoch $M_{BH}$ Estimates

$$M_{BH} = f \frac{RV^2}{G}$$

$R - L$ relationship yields black hole mass with one spectrum and two measurements:
1. emission line width ($\nu$)

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Single Epoch $M_{BH}$ Estimates

\[ M_{BH} = f \frac{RV^2}{G} \]

The $R - L$ relationship yields black hole mass with one spectrum and two measurements:
1. emission line width ($V$)
2. AGN $L \rightarrow$ proxy for $R$
Single Epoch $M_{BH}$ Estimates

\[ M_{BH} = f \frac{RV^2}{G} \]

$R - L$ relationship yields black hole mass with one spectrum and two measurements:
1. emission line width ($V$)
2. AGN $L \rightarrow$ proxy for $R$

ALL mass estimates for AGNs using emission lines are based on the local observed $R - L$ relationship for H$\beta$
AGN Luminosities – Host Galaxy Starlight

5’ x 5’ images

NGC 4051
z = 0.00234

Mrk 79
z = 0.0222

PG 0953+414
z = 0.234

Large slit (i.e. 4”x10”) used to minimize aperture effects → strong starlight contamination at low z
Updates to RM Database

MDM 2007

Denney et al. 2010

LAMP 2008

Bentz et al. 2009

Hβ Results Summary:
1 new object
3 replacements
2 additions

Hβ Results Summary:
7 new objects
1 addition

HST Cycle 17 WFC3 Imaging Campaign
Updated Radius - Luminosity Relationship: Preliminary Version

New and replacement measurements in color

Bentz et al. 2011, in prep
Kaspi et al. 2007

CIV R-L Relationship

Only 7 AGNs, and 5 have similar luminosities

Slope of CIV R-L is consistent with slope of H\(\beta\) R-L

Not enough MgII measurements for R-L relationship
Summary

- Reverberation mapping substitutes time resolution for spatial resolution and probes the gravity of the BH
- RM masses consistent with dynamics and with Bayesian modeling
- We are just beginning to acquire data that could soon allow direct constraints on the detailed physics of the BLR gas
- The R-L relationship provides a convenient method for estimating $M_{\text{BH}}$ in any broad-lined AGN
Some Big Questions:

1. What is the origin of the BLR?

2. What systematic errors are inherent in AGN black hole masses?

3. What (if any) is the role of radiation pressure in the BLR?

4. What is the range of physical characteristics (and $f$ values) among BLRs?

5. What are the differences between the optical BLR and the UV BLR (e.g. kinematics or wind launching)?

6. What (if any) are the physical differences between low-z and high-z AGNs?