

Systematic Errors in Black Hole Mass Measurement Using Reverberation Mapping

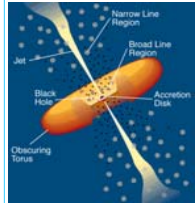
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Abstract

The goal of this project is to explore how a measurement of the black hole mass, using reverberation mapping, within an active galactic nucleus (AGN) changes due to systematic effects inherent in using both a wind-based AGN model, as well as combination wind-disk model. This aim is to address two specific questions. First, how does the black hole mass measurement change when we characterize the broad-line region (BLR) by only two numbers that characterize the velocity dispersion of the emitting gas and the mean reverberation response time? The BLR is a complex region and we aim to determine how much information one loses through a simplified characterization. Second, how does the geometry of the wind affect the measurement of the black hole mass? Specifically, we explored the effects of changing the opening angle of a conical wind and its inclination with respect to an Earth-based observer. These questions are important to help discern the structure of the BLR. This model will help to gather intuition about how the geometry and kinematics of the BLR affect a black hole mass measurement obtained through reverberation mapping.

Active Galactic Nuclei



Active Galactic Nucleus (AGN): An extremely energetic central region of a galaxy whose brightness cannot be attributed to stars alone. A typical AGN emits at least the same amount of energy that is emitted by an entire galaxy of stars, but in a much smaller volume.



Figure 2: Jet from M87, taken by the Hubble Space Telescope

Figure 1: Basic AGN Structure

Structure

Central Engine: Supermassive black hole with matter actively accreting onto it

Broad Line Region (BLR): Relatively dense region of line-emitting gas near to the central engine

Narrow Line Region (NLR): Relatively low density region of line-emitting gas much farther away from the central engine

Obscuring Torus: Region of dust surrounding the central engine, most likely toroidal

Jet: Relativistic outflow from the central engine

Reverberation Mapping

When there is a radiative event in the central engine, the BLR lines will respond after some time delay, τ .

$$\tau = \frac{r}{c} (1 + \cos\theta)$$

Equation 1: Relation for an isodelay surface

Ellipsoidal surfaces of constant time delay are known as isodelay surfaces. An Earth-based observer, however, is effectively an infinite distance away from the AGN, so these are essentially paraboloidal surfaces. A cross section of this is shown in Figure 3, for which the time delay is given by the polar equation for a parabola (Equation 1).

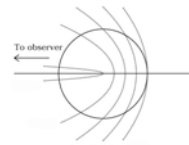


Figure 3: Isodelay surfaces

The mass of the black hole, shown in Equation 2, is found using a virial relation, where $r = c \tau$ (τ is the time delay), $\sigma = \Delta v$ is the velocity dispersion, and f is some scaling factor on the order of unity depending on the geometry and kinematics of the BLR.

$$M = \frac{f r \sigma^2}{G} \rightarrow M = \frac{f c \tau (\Delta v)^2}{G}$$

Equation 2: M- σ relation to find the mass of a black hole using reverberation mapping

Creating the Model

- Wind geometry: conical with opening angle ω
- The wind is moving radially, using two simple velocity distributions, shown in Equations 3 and 4
- Step outward in r and ω (i.e., place clouds at each step)
- For each step, transform from the AGN frame to the frame of an Earth-based observer
- Inputs: M , r_{\min} , r_{\max} , ω_{\min} , ω_{\max} , α , i , A , steps in r , steps in ω , v_{\max} , r_{\max}
- Outputs: 1D Transfer Function, Velocity Profile, 2D Velocity Delay Map
- Transform the simple model into a Monte Carlo simulation using a random number distribution weighted like $\sin(\omega)$ (i.e. BLR clouds randomly placed throughout opening angle range, weighted like $\sin(\omega)$)

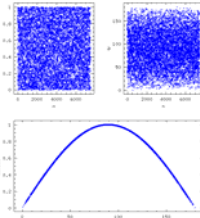


Figure 4: Random Number Distribution for Monte Carlo Simulation

$$v(r) = \left(\frac{v_0}{r_{\min}} \right) r$$

Equation 3: Ballistic Velocity Distribution

$$v(r) = \sqrt{\frac{GM}{r}}$$

Equation 4: Escape Velocity Distribution

Spherical Test Case

Tested the model against results for a spherical wind from Welsh and Horne, 1991, using both a ballistic $v(r)$ and escape velocity $v(r)$.

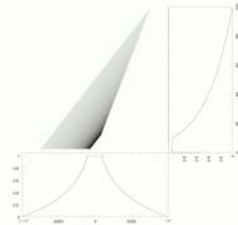


Figure 5: Ballistic Model, Monte Carlo Simulation

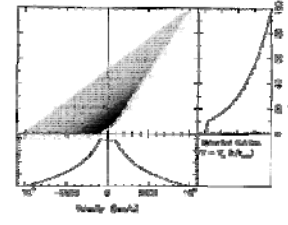


Figure 6: Ballistic Model, Welsh & Horne 1991

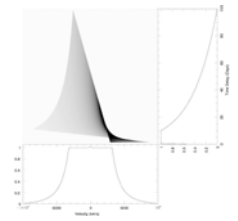


Figure 7: Escape Velocity Model, Monte Carlo Simulation

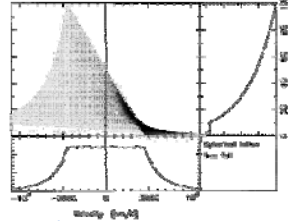


Figure 8: Escape Velocity Model, Welsh & Horne 1991

Disk Wind-Like Geometry



Figure 9: Geometry for $75^\circ \leq \omega \leq 90^\circ$

Clouds randomly placed within narrow opening angle range near the disk plane of the AGN

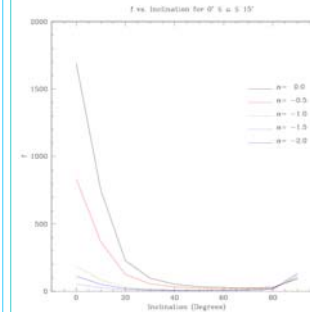


Figure 10: f vs i for $75^\circ \leq \omega \leq 90^\circ$

Jet-Like Geometry

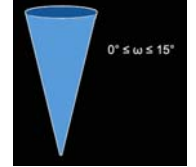


Figure 11: Geometry for $0^\circ \leq \omega \leq 15^\circ$

Clouds randomly placed within narrow opening angle range near the z-axis of the AGN

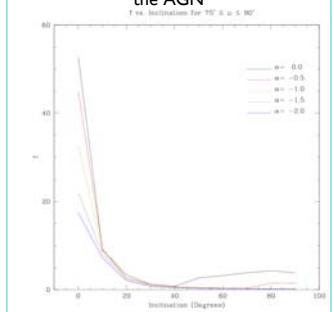


Figure 12: f vs i for $0^\circ \leq \omega \leq 15^\circ$

Conclusions and Future Work

We expect f to be on the order of 1. For the two extreme cases of opening angle ranges discussed here, the value of f is orders of magnitude larger than this expectation, especially for low inclinations. This indicates that, if the BLR were purely wind-based, a wind that is between $0^\circ \leq \omega \leq 15^\circ$ or $75^\circ \leq \omega \leq 90^\circ$ is physically absurd. Thus, further exploration of a wind-based BLR should exclude these two extreme cases.

Future work on this project will include the addition of a disk component to the wind model. These two components sum linearly, so this should be fairly straightforward. Additionally, improvement of the resolution of the model will be achieved by simulating more values of α and different opening angle ranges. Finally, we will attempt to better understand the effects of our extensive simplification of the BLR.

Bibliography and Acknowledgements

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