Mass of the Central Black Hole of Active Galactic Nuclei: Reverberation Mapping

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Mass of the Central Black Hole of Active Galactic Nuclei: Reverberation Mapping

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Abstract

Information about Active Galactic Nuclei (AGN's) mass can help to know more about the host galaxy's evolution. Using reverberation mapping, we can determine the 'primary' mass of the AGN. Here primary mass refers to the mass determined by motion of the nearby gas. In this study we retrieved spectral data of five Active Galactic Nuclei (AGN) to get these data. We fit two 2D Gaussian curves for a narrow line and a broad line region of the AGN spectra to determine the mass.

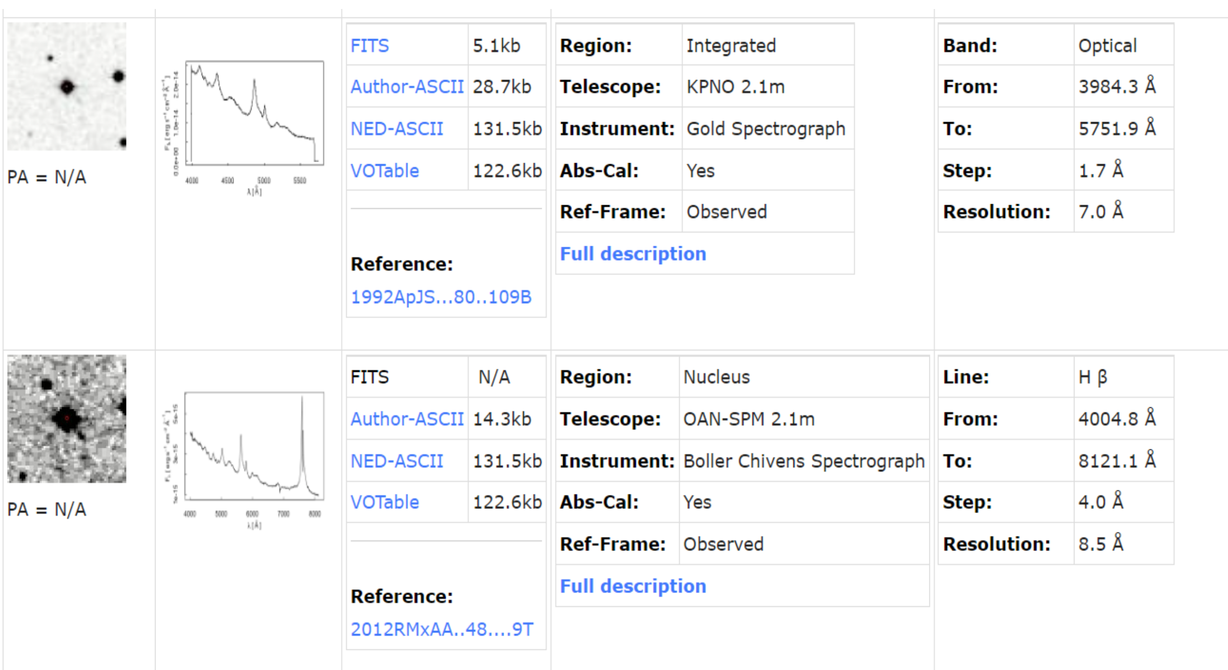
Introduction

Most of the galaxies host supermassive black holes in their center. The mass of these black holes appears to be linked to the stellar velocity dispersion in the bulge, the bulge mass, and bulge luminosity. Black holes may play a fundamental role in galaxy evolution but the exact details are still unclear. Beyond the local universe, black hole masses are measured through indirect methods in Active Galactic Nuclei (AGN) [1]. Many galaxies have very bright nuclei, so bright that the central can be more luminous than the remaining galaxy light. These nuclei are called Active Galactic Nuclei, or AGN for short. The unified model of an AGN consist of an accretion disk, fast-moving gas clouds in the vicinity of black hole (the broad line region; BLR) surrounded by a dusty torus, and more slowly moving gas residing on galactic scale that is photoionized by the central source (the narrow line region; NLR) [2]. Black hole masses are estimated through an application of virial method, where the BLR clouds are assumed to be following the gravitational potential of the black hole. BLR are illuminated by the light of the accretion disk. This excites the electrons in their atoms, which re-emit an emission line spectrum. Where we can see the permitted lines of spectrum. Due to the position of BLR clouds its orbital motion broadens these spectral lines through the doppler effect[1].

In this work, we have taken five different type-1 AGN spectra. Where we are going to use BLR, to measure the mass of the black hole.

Data

In this article we used the data of five AGNs namely 3C 273, NGC 5548, NGC 4235, NGC 7469 and NGC 1068. The raw data for these AGNs were taken from the NASA/IPAC Extragalactic Database. The Wavelength (Å), Intensity (erg/cm^2/s/A) and Uncertainty (erg/cm^2/s/A) (if given any) of the corresponding AGNs are the data that were used during modeling. The intensity refers to the energy per unit area per unit time per unit wavelength. The z (Helio) value of the corresponding AGNs were extracted from the NASA/IPAC Extragalactic Database. Using the z (Helio) value and via Ned Wright's Javascript Cosmology Calculator (ucla.edu), the Luminosity Distance (dl) of the corresponding AGNs can be calculated. The AGN's previously determined mass was compared from previously published research articles. The whole code and clean data can be found in this repository.



PA = N/A	FITS	5.1kb	Region:	Integrated	Band:	Optical
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	NED-ASCII	131.5kb	Instrument:	Gold Spectrograph	To:	5751.9 Å
	VOTable	122.6kb	Abs-Cal:	Yes	Step:	1.7 Å
			Ref-Frame:	Observed	Resolution:	7.0 Å
	Reference: 1992ApJS...80..109B		Full description			
PA = N/A	FITS	N/A	Region:	Nucleus	Line:	H β
	Author-ASCII	14.3kb	Telescope:	OAN-SPM 2.1m	From:	4004.8 Å
	NED-ASCII	131.5kb	Instrument:	Boller Chivens Spectrograph	To:	8121.1 Å
	VOTable	122.6kb	Abs-Cal:	Yes	Step:	4.0 Å
			Ref-Frame:	Observed	Resolution:	8.5 Å
	Reference: 2012RMxAA..48....9T		Full description			

Fig: Spectra list of 3C 273 from the NASA/IPAC Extragalactic Database.

From this list, we took a single spectra to analyze. Nucleus Region Spectra was taken. We also took the smallest resolution available. The wavelength ranges from 4000Å to 5500Å.

Methodology

This research project is intended to investigate the approach to measure the mass of black holes using the region which produces broader emission lines named Broad Line Region. In the process used in this project, the radius, geometry and orbital speed of the cloud are required to determine the black hole's mass.

It is assumed that the motion of broad line clouds in elliptical orbit follows Kepler's law of Orbital Motion. But in this case, it is not possible to have the motion of a single cloud. Here, a doppler shift of the spectrum of all the BLR clouds together is used to measure the speed. The BLR clouds seem to have a shape of flattened disk in spherical distribution and so it may be observed at some angle to the orbital plane. Therefore, to describe the geometry of the Broad Line Region, virial factor (f) is included. Its value can vary for different types of AGN spectra. Here, for a spherical distribution, the value of the virial factor is ¾ for all the AGNs.

$$M_{BH} = f\frac{R_{BLR}v^2}{G} \quad (1)$$

Broad Line Region Radius:

A concept called reverberation mapping is a method to measure the structure of the Broad Line Region surrounding a supermassive black hole at the center of an active galaxy. According to this concept, the radius and the optical luminosity are related. Luminosity can be obtained from the spectrum at a wavelength of 5100 A. It is an area of continuity without any spectral lines.

$$log(\frac{R_{BLR}}{light\ day}) = 1.527 + 0.533\ log(\frac{\lambda L_{\lambda}(5100\ Å)}{10^{44}\ erg/s}) \qquad (2)$$

Here,

$light\ day = 2.59 \times 10^{13}$ meters

$L_{\lambda}(5100\ Å)$ = Luminosity Density at 5100 Å

λ = Wavelength

Broad Line Region Velocity:

The width of a spectral line emitted from the Broad-Line Region will be used to calculate Broad Line Region Velocity from the spectrum. The Full Width at Half-Maximum (FWHM) of the line provides a good rough estimate of the orbital speeds.

This makes use of the presumption that the doppler shifting causes the width. The Doppler equation in general form is,

$$\frac{\lambda_{obs}}{\lambda_{src}} = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} \qquad (3)$$

Here,

λ_{obs} = Observed Wavelength

λ_{src} = Wavelength Emitted by the Source

v = Cloud Velocity

c = Speed of Light

When the cloud velocity is much smaller than the speed of light, $v << c$, then the preceding equation simplifies to,

$$\frac{v}{c} \approx \frac{\Delta\lambda}{\lambda_{src}} \tag{4}$$

Rewriting the preceding equation, as $\Delta\lambda = \lambda_{obs} - \lambda_{src}$ which is FWHM in units of angstrom and the observed wavelength of the Hβ line is 4863 Å,

$$v = \frac{c\, FWHM(H\beta)}{4863\ \text{Å}} \tag{5}$$

Thus, the cloud velocity of the broad line region is obtained. The method of reverberation mapping applied here is based on a book chapter authored by Timothy Hamilton[3].

Analyzing Techniques

In our project, we employed various methods and techniques to estimate the mass of the black hole in five active galactic nuclei (AGNs) including the well-known 3C 273. Our approach involved studying the emission spectra of the AGN and fitting a model to the observed data. This allowed us to extract important parameters and make inferences about the black hole's mass.

In the raw data of 3C 273 from NASA/IPAC Extragalactic Database, there were measurements of the flux density at different wavelengths. The data consisted of two main columns: the observed spectral axis, representing the wavelength, and the observed intensity, representing the flux density of the emitted light. As the observed data is affected by the redshift of the object, we applied a redshift correction by dividing the wavelength by (1+z) and multiplying flux density by (1+z), where z is the redshift value of the object. This conversion transformed the data into the source frame, allowing us to analyze the emission lines at their rest wavelengths. We also converted flux density to luminosity density by multiplying flux density by 4, pi, and source distance squared, which is the area of a sphere of radius d (distance from the observer to the source).

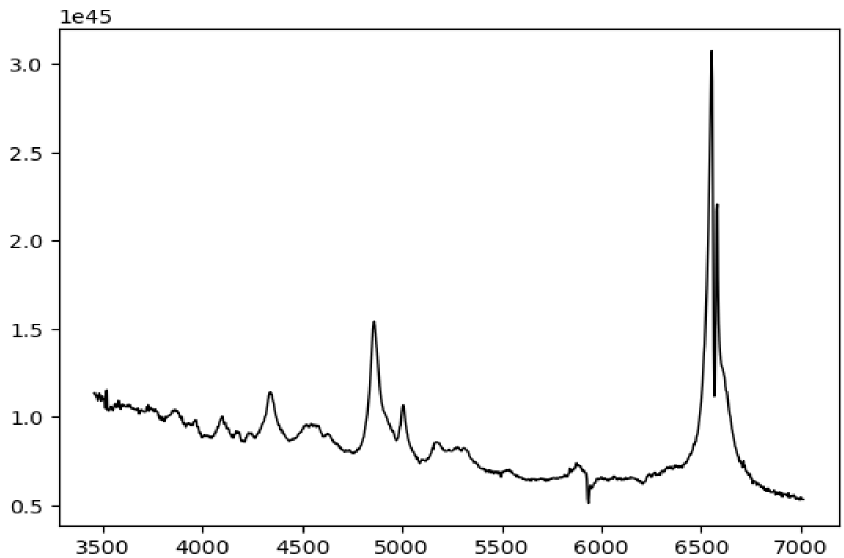

Figure 1: Intensity vs Wavelength graph of 3C 273

We defined Gaussian functions to model the Hydrogen-beta Narrow, Hydrogen-beta Broad, Oxygen(III) Narrow, and Oxygen(III) Broad emission lines observed in the AGN spectra while fitting the overall curve. The parameters of the Gaussian functions, such as amplitude, mean, standard deviation, and constant(height of the baseline of a Gaussian), were optimized using the curve fitting function provided by the scipy library of Python. By fitting this model to a selected data region including wavelength 5100 Å, we obtained the best-fit parameters that described the emission lines.

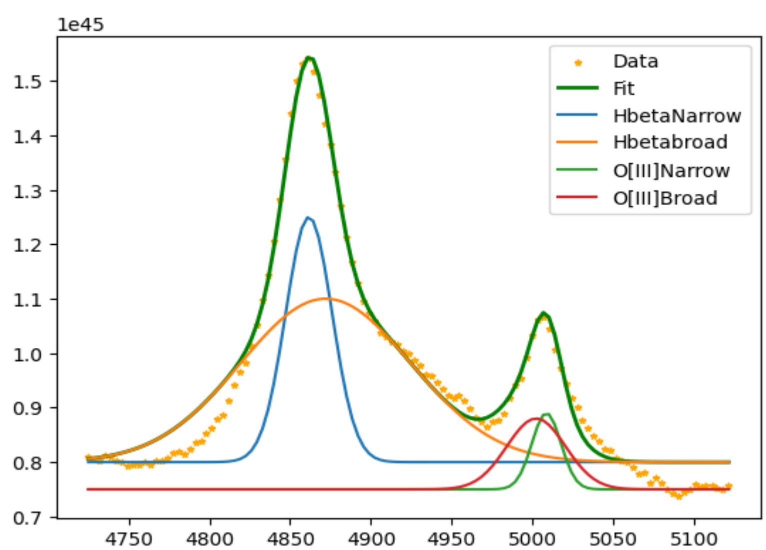

Figure 2: Fitted curve of various emission lines.

We used the virial mass formula to estimate the black hole mass (M_BH) in our study. The formula can be expressed as

$$M_{BH} = f\frac{R*v^2}{G} \qquad (6)$$

This formula connects the mass of the black hole with the velocity dispersion (v) of gas in the broad-line region (BLR), the radius (R) of the BLR and the virial factor f. We calculated the velocity dispersion (v) based on the Full Width at Half Maximum (FWHM) of the Hbeta broad emission line. Additionally, we estimated the radius (R) using a scaling relation involving the luminosity of the O[III] line at 5100 Å.

Results & Discussion:

We have analyzed a total of 5 AGN spectra. Below is a table of the masses we got and the mass of the central Black Hole from other studies. Masses are in the solar mass units.

AGN	3C 273	NGC 5548	NGC 4235	NGC 7469	NGC 1068
We got	8.52×10^8	3.466×10^6		1.037×10^6	2.173×10^6
Other studies	6.59×10^9 [7]	5.0×10^7[5]	2.5×10^7[8]	1.78×10^7[6]	1.5×10^7 [4]

We could not fit the continuum to the spectral data of the AGN. Which introduces uncertainty to the FWHM of the H_β broad & narrow line components. The mass of the central BH of the AGN is proportional to the square of the FWHM of the H_β broad line components. So, this fact primarily contributes to the mass inconsistency with the other studies. This fitting uncertainty is negligible while finding the luminosity at 5100 A^o. Another source of uncertainty is the virial factor. We have used the virial factor $f = 3/4$ for all these AGNs, which is very unlikely. $H\beta$ emission of NGC 4235 is not prominent enough to resolve the FWHM of the broad line of the $H\beta$ line. We only fit a short region around the $H\beta$ line. So, this could be another source of error as we did not fit the whole spectrum.

Conclusion:

This study aimed to estimate black hole masses in AGNs using reverberation mapping. The difficulty in fitting the continuum of AGN spectral data leads to uncertainty in the measurement of FWHM, which in turn affects the calculations of black hole masses. Furthermore, employing a fixed variable factor contributes to the significant amount of error. Despite all of these, this research highlights the significance and potential for improvement in black hole mass determination through reverberation mapping.

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