Exploring the Relationship between Galaxies and their Supermassive Black holes

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Declaration

We, Mr Siddarth of Ramaiah University of Applied Sciences, Bangalore, Mr Akshat Gupta of Delhi Technological University, Delhi, Miss Sameera Rayapudi and Mr Sanjay R of Amrita Vishwa Vidyapeetham, Coimbatore, Miss Ashvika Saroja G of PSG College of Technology, Coimbatore, Mr Arun Prasath Srinivasan of D.G. Vaishnav College, Chennai, Mr Nishant Kumar Yadav of Jaypee Institute of Information Technology, Noida, Mr Vishnu Narayan M of Loyola College, Chennai, Miss Aleena Reji and Miss Aparna J of Assumption College, Changanacherry, Mr Sirswa Kuldeep Shree Ram of IISER Kolkata, Mr Ronald Albert Mathew of St Thomas College, Pala and Mr AnanthaVishnu, hereby declare, this research internship work entitled ***"Exploring the relationship between Galaxies and Supermassive Black holes"*** *has been carried out by us under the guidance of Mr Sundar, our mentor in the field of Astrophysics and Mr Pavan Kumar AV, who is pursuing a PhD from IMT school of advanced studies, Lucca.*

Acknowledgements

This entire project was made with the underlying idea of the paper done by Dr Laura Ferrarese which studies the relationship between the mass of the black hole and its host galaxy's stellar velocity dispersion. Therefore we thank Dr Ferrarese for observing such a significant relationship between the two galactic components and thus opening our eyes to a very important astronomical observation. We would also like to thank Dr John Magorrian for his efforts in observing the significant relationship between the mass of the black hole and the mass of the bulge of the host galaxy. We would also like to thank our mentor, Dr Sundar MN, for assisting us throughout the internship and pushing us forward when things went awry. We would also like to thank Miss Amaria Bonsi Navis for her continuous belief in us even when we were struggling at some points in the research. We thank the whole Society for Space Education Research and Development group including Mr Mahesh, Miss Nikitha and Mr Pawan for helping us extend our knowledge on various aspects of the Scientific Research world and for presenting us with an opportunity of a lifetime. Finally, we extend our team's gratitude to all our fellow scientific compadres actively participating in this SSERD internship across various fields, for all their hard work in their projects. We hope for continued exploration into the unknown and testing the boundaries of human knowledge.

Abstract

We present a sample of spheroidal and elliptical galaxies with low stellar velocity dispersion values, whose central supermassive black hole masses have been measured by various methods such as stellar kinematics, gas kinematics, reverberation mapping, virial theorem to BLR cloud and BLR of AGN and optical continuum luminosity. We have compiled data for the estimated stellar velocity dispersion and masses of black holes at the centre of 18 galaxies that fit our chosen criteria. We also compiled the available data for bulge masses of the said galaxies, so that we could have a better understanding of how the mass of the central black hole and the central bulge affect the stellar properties of galaxies. Subsequently, the values for $\log(M_{BH}/M_0)$ and $\log(\sigma)$ were plotted using Python and the graph for M-σ relation (Ferrarese and Merrit, 2000) was obtained. Further, $\log(M_{BH}/M_0)$ and $\log(M_{Bulge})$ was also plotted using Python alongside to obtain the M_{BH} - M_{Bulge} relation (Maggorian, 1998) to have a better perspective. Our results indicate that the correlation is loose between the $\log(\sigma)$ vs $\log(M_{BH})$ for low values of σ in the chosen data, whereas the correlation between $\log(M_{BH})$ vs $\log(M_{Bulge})$ appears to be much tighter for our considered dataset. In addition to this, we also present the possible causes for the deviances using the observations obtained from this study, especially due to the limitations of the chosen dataset.

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Introduction

Galaxies have been found to be hosts to supermassive black holes that exist at their centres. There exist many relations between a galaxy's properties such as rotational energy, stellar velocity dispersion, dark matter halo, the mass of bulge of a galaxy and arm pitch angle and the properties of its central black hole. One such correlation has been observed between the mass of the supermassive black hole and the stellar velocity dispersion of the host galaxy. The correlation is known as M - σ relation,(Merritt and Ferrarese, 2000) where M is the mass of the supermassive black hole and σ is the stellar velocity dispersion of the host galaxy.

The M - σ relation is an important factor in the astronomical researches that shed light on the co-evolution of galaxies and their central black holes. Theoretical models proposed to explain the M - σ relation are based on physical mechanisms such as—viscous disk accretion, adiabatic black hole growth, gas or dark matter collapse, stellar capture by accretion disks, dissipationless merging, unregulated gas accretion and the self-regulated growth of black holes by momentum or pressure-driven winds.[1]

Another correlation that has been observed is the M_{BH} - M_{Bulge} relation (Maggorian, 1997) which exists between the masses of supermassive black holes and the masses of the bulges of the host galaxies. It is suggested that a common mechanism links the growth of these two galactic components in the correlation, with galaxy mergers being the most likely candidate from the proposed evidence(Larson, 1979).

1.1 | Motivation

Even far in the past, the night sky is the most inquisiting topic for humanity. Many questions arise with the increasing curiosity of humankind. Some of those questions are—What force kept these galaxies or bulges intact? What is the role of supermassive black holes in the formation of these bulges? Is there any relation, which explains some connections between masses of central supermassive black holes and the bulges of the host galaxies? But now, with the help of increasing understanding and technologies, we can answer those questions. In the past three decades, humankind moved forward from confirming the existence of black holes to explaining the significant role of these black holes in their host bulges. In these few decades, scientists and researchers approached these problems using different methods. Some of those correlations exist between rotational energy, velocity dispersion, dark matter halo, the mass of SMBH, the mass of bulge, an arm pitch angle, etc. We focus on the correlations between supermassive black holes and their host galaxies. Some of these relations we are going to discuss are mass of SMBH-velocity dispersion of bulge relation (i.e., M_{BH}-σ relation) and mass of SMBH-mass of bulge relation (i.e., M_{Bulge}-M_{BH} relation). Using these relations, we would like to understand the forces that bind stars and other celestial bodies within these bulges and to understand black holes role within these bulges.

1.2 | Aim and Objective

In this project, the galaxies that we have chosen for M - σ relation have stellar velocity dispersion in the range of σ < 150 km/s i.e. low stellar velocity dispersion as we found it to be less common. Through this project, we make an attempt to make an introductory analysis on the M - σ relation for galaxies with low stellar velocity dispersions, by plotting their values against the masses of their respective black holes along with a simultaneous study of the nature of M_{BH} - M_{Bulge} relation for the same set of galaxies.

2

Literature Survey

2.1 | Stellar velocity Dispersion

The Stellar Velocity Dispersion σ is the statistical dispersion of velocities about the mean velocity for a group of celestial objects like a cluster, galaxy or a supercluster. By measuring the radial velocities of these objects through astronomical spectroscopy. stellar velocity dispersion can be calculated. Radial velocities are estimated using Doppler's effect with spectral lines of the collection of objects. The more the radial velocity one measures, the more is the accuracy of knowing their dispersion. This relation turned out to be very useful in estimating the masses of thousands of black holes.

2.2 | Methods of Measurement for M_{BH}

Stellar Kinematics :

Stellar kinematics is the study of the locomotion of stars in the cosmos. Stellar kinematics takes into account all the mensuration of stellar velocities of our galaxies and its subcomponents as well as the internal kinematics of other distant galaxies. Study of the motion of stars in different subcomponents of the Milky Way, provides information about the emergence and progression of our galaxy and other distant galaxies. Stellar Kinematic measurements can also unravel several phenomena such as hypervelocity stars eloping from our galaxy , which are portrayed as results of gravitational confrontation of binary stars with the SMBHs at the Galactic Center. It was suggested that Stellar Kinematics of stars can be explained by a gradual decay of trouble motions as is predicted by possible collapse models and have shown a relation with metallicity and stellar velocity dispersion. Stellar-kinematic data is quite often used to study their evolution and mass distributions, and to detect the presence of dark matter or SMBHs through their gravitational influence on stellar orbits.

Gas Kinematics : Gas Kinematics provide salient indications to the dynamical structure of galaxies and hold impediments to the processes driving their progression. In early-type disc galaxies, ionized gas tends to rotate faster than stars and to have a lower velocity dispersion ($V_g \geq V*$ and $\sigma_g \leq$ ß), whereas, in late-type spirals, gas and stars show almost the same rotation velocities and velocity dispersions ($V_g \approx V*$ and $\sigma_g \approx$ß).

Reverberation Mapping : Reverberation mapping is an approved approach that is used to estimate the expanse of the BLR and central black hole mass in AGN and thus finding the black hole's mass. The idea behind reverberation mapping is to understand the structure and kinematics of the BLR by observing the precise response of the broad emission lines to changes in the continuum.Reverberation mapping can also allow us to determine the nature and flow of line-emitting gas in active nuclei and to judge accurately the structured uncertainties in reverberation-based black hole mass measurements.

Virial Theorem to BLR Cloud and BLR of AGN : In type-1 AGNs, the virial theorem is the technique to estimate the black hole mass. In this method, the cloud velocity is usually deduced from the width of the broad lines, and the size of the BLR is inferred from reverberation mapping measures.

2.3 | M - σ relation

The M - σ relation is a well established fundamental relationship that shows the relation between supermassive Black holes (SMBHs) and their host galaxies. The M - σ relation shows a connection between SMBHs and stellar kinematics of galactic spheroids, i.e. the correlation between the mass of the black hole M_{BH} and the stellar velocity dispersion of host bulges σ .The existence of SMBHs has been confirmed in more than 85 galaxies. A supermassive black hole is one with a mass on the order of 10^6 solar masses and above. So as far as the existence of black holes is confirmed there should be a good correlation showing the influence of black holes on host galaxies and vice versa. Thus, the M - σ relation came into play.

This relation was first presented in a paper published by Ferrarese and Merritt in the

year 2000. The M_{BH} - σ relation locally is a tight, power-law correlation with logarithmic slope originally estimated to be in the range $\beta \approx 3.75 - 4.8$. Robertson (2005)
Mass of a black hole shows correlation with different parameters of the host like mass, luminosity, velocity dispersion etc. Many works were proposed to give a relation for black hole mass, like the relationship between galaxy luminosity and black hole mass etc. But all such relations had comparable levels of scatter. However, the M-σ relation gives a strong correlation between the SMBH mass and host galaxy properties.

The equation given below is the proposed form of M-σ relation:

$M/10^8\text{Mo} \approx 3.1(\sigma/200km^{-1})^4$ (David, 1999)

This is called Faber - Jackson Relation for black holes where, M is the mass of supermassive blackhole, M_0 is the solar mass and is the stellar velocity dispersion. The tightness of M-σ relation points to some kind of mechanical feedback that maintains the connection between blackhole mass and velocity dispersion, in spite of processes which might increase the scatter over time like galaxy mergers and gas accretion. The interpretation of these correlations has led to the development of the field of active galactic nucleus (AGN) feedback on the host galaxy, and the co-evolution between SMBHs and their host galaxiesZubovas (2019). In the paper published in 2000(Ferrarese and Merritt) the M-σ relation was studied for stellar velocity dispersion 200 km/s and black hole mass of the order 10^8 M_0. Before the relation was observed, a large discrepancy existed between the 3 methods used in calculating the mass of black holes which are namely given by :

1. Direct or dynamical measurements based on the motion of stars or clouds of gases near the black hole . This technique used to give masses that averaged nearly 1%of the bulge mass("The Magorrian Relation")
2.Reverberation Mapping in the AGN being the second technique .
3.Soltan Argumen being the third technique.

Both the above techniques gave the mean value of M_{BH}/M_{Bulge} that was a factor $\approx$ 10 as what was implied by the Magorrian Relation.

Then the M - σ relation was discovered and solved this discrepancy. The M_{BH}/M_{Bulge} ratio in big early-type galaxies is now considered to be nearly 1:200 and increasingly smaller as one moves to less massive galaxies(Merritt, 2013).

2.3.1 | Plot for M - σ relation

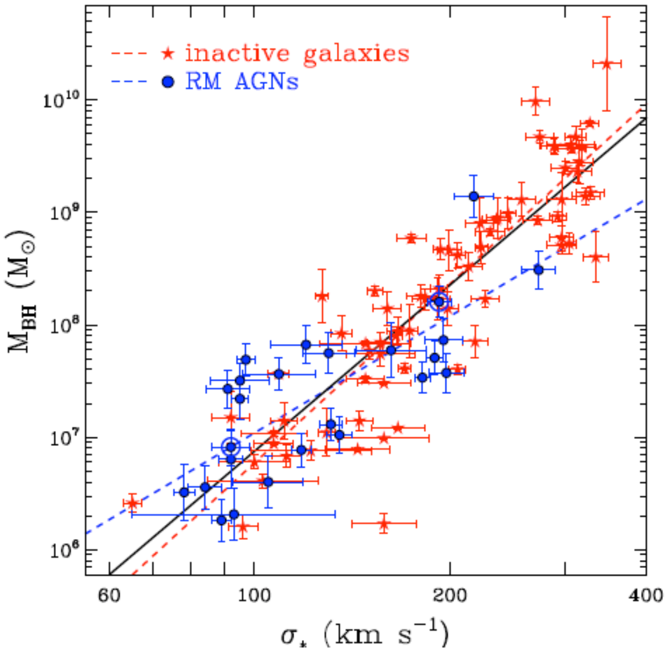

Figure 2.1: Black hole – galaxy scaling relations and gas outflow; Jong-Hak Woo (2013)

Black-hole mass plotted against velocity dispersion of stars in a galaxy bulge. Points are labelled by galaxy name; all points in this diagram are for galaxies that have a clear, Keplerian rise in velocity near the center, indicative of the presence of a central mass. The M–σrelation is shown with the solid black line in the plot.

2.4 | M_{Bulge} - M_{BH} relation

All large galactic bulges have central black holes, the mass of which is proportional to the bulge stellar mass, $M_{BH} \approx 0.001 M_B$ where M_{BH} represents the mass of the black hole and MB represents the bulge mass of a particular galaxy. The formation of central black holes and bulges of galaxies happens in the same period. This implies that their formation is closely related. When dust/gas falls into the black hole, enormous amounts of energy are released. This process of matter falling into an object under gravity is called accretion. Accretion releases energy upto 10% of the rest mass energy of the material falling into it as photons or radio-luminous jets. In very rare cases, the energy thus released from the black hole heats up the gas content in the bulge and blows away the gas and dust, stopping the formation of new stars in those bulges. Cattaneo (2009)

The M_{Bulge} - M_{BH} relation was first observed by Magorrian et al. (1998). In the above work, they have studied 32 galaxies and observed a steeper dependence of the mass of the black hole and the bulge mass for core galaxies and derived an equation that gives a 68% of confidence bounds.

$$\log[M_{BH}, fit/M_o] = (-1.79 \pm 1.35) + (0.96 \pm 0.12) * \log[\frac{M_{Bulge}}{M_o}].$$

(John Magorrian, Scott Tremaine et al.1998)

This equation evolved as time progressed, with the discoveries of new galaxies and their bulge and black hole masses.

The best-fitting normalization of the $M_{BH} - M_{Bulge}$ relation was found to be $M_{BH} = 0.0012 M_{Bulge}$ in 2001 in a famous paper published by R. J. McLure and J. S. Dunlop, in agreement with recent black hole mass studies based on stellar velocity dispersions at that time.R. J. McLure (2002)

In 2004, Nadine Häring and Hans-Walter Rix re-examined the equation with 30 more galaxies and found that $M_{BH} \sim M_{\mathrm{bulge}}^{1.12\pm0.06}$

with an observed error scatter of ≤ 0.30 dex (a fraction being measurement errors). This relation is derived from a bisector linear regression fit to the data.

$$\log[\frac{M_{BH}}{M_{Sun}}] = (8.20 \pm 0.10) - (1.12 \pm 0.06) * \log[\frac{M_{Bulge}}{M_o}].$$

In 2013, an updated sample of 72 early-type galaxies was taken and its data was used to compute the M_{BH} - M_{Bulge} equation by Nicholas J. McConnell and Chung-Pei Ma.

For the power-law galaxies using the whole data, the best fitting gave

$$\log_{10}[M] = (8.46 \pm 0.08) + (1.0 \pm 0.11) * \log[\frac{M_{Bulge}}{10^{11} * M_o}].$$

Also in the early,core type galaxies,

$$\log_{10}[M] = (8.45 \pm 0.15) + (1.09 \pm 0.20) * \log[\frac{M_{Bulge}}{10^{11} * M_o}].$$

with minimum error mark= 0.28dex

And for early, power law type galaxies,

$$\log_{10}[M] = (8.43 \pm 0.20) + (0.94 \pm 0.39) * \log[\frac{M_{Bulge}}{10^{11} * M_o}].$$

with minimum error mark= 0.50dexMcConnell and Ma (2013)

2.4.1 | Plot for M_{Bulge} - M_{BH} relation

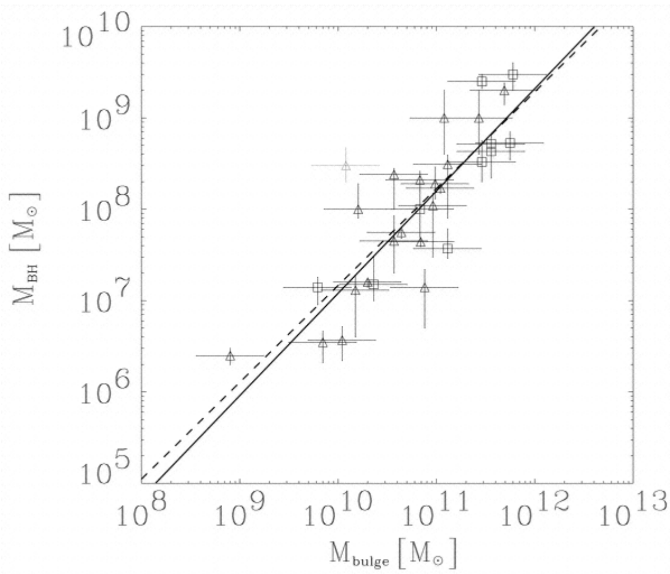

Figure 2.2: The Relation between Black Hole Mass, Bulge Mass, and Near-Infrared Luminosity; Marconi & Hunt; 2003Hunt (2003)

Blackhole mass vs. bulge mass for the 30 sample galaxies. The solid line gives the bisector linear regression fit to the data with a slope of 1.12 ± 0.06. For comparison, the relation found by Marconi & Hunt (2003) is shown as the dashed line (slope: 1.06 ± 0.09).

3

Data and Methodology

3.1 | Data

We had hoped to establish the significance of the said M-σ relationship for the lower stellar velocity dispersions, for which we studied various papers that have studied galaxies with low stellar velocity dispersions (all of which have been referenced along with table 3.1) and tabulated them in Table 3.1.

Table 3.1: Mass of Black holes and Stellar Velocity Dispersion

Galaxy	**Mass of the Black hole (Mbh)** 10^6 **Mo**	**Method**	**Velocity Dispersion** σ**(km/s)**	**Reference**	**Log Mbh/Mo**	**Log** σ	**Bulge mass** 10^9 **Mo**	**Log Bulge mass**
NGC 221	2.5 ± 0.5	s	72 ± 4	[a]	6.397	1.85	2.9 ± 3	9.46
NGC 4151	30^{+10}_{-20}	s,g	97 ± 10	[a]	7.477	1.98	$13^{+0.6}_{-0.5}$	10.11
NGC 7457	$3.5^{+1.1}_{-1.4}$	s	80 ± 5	[a]	6.544	1.90	7.0	9.84
NGC 4742	14^{+4}_{-5}	s	109 ± 5	[a]	7.14	2.03	6.2	9.79
NGC 4486A	13^{+4}_{-7}	s	10 ± 10	[a]	7.11	2.04	-	-
NGC 6221	2.88	B-A	64 ± 2	[b]	6.46	1.80	70	10.84
NGC 7465	3	B-A	95 ± 4	[b]	6.477	1.97	-	-
ESO 234-G050	1.2	B-A	69 ± 1	[b]	6.00	1.838	-	-
MrK 335	8.61	V-BLR	64 ± 17	[c]	6.935	1.80	53.7	10.73
UGC 3478	0.81	V-BLR	89 ± 18	[c]	5.90	1.94	-	-
IRAS 766	0.83	V-BLR	64 ± 20	[c]	5.91	1.80	-	-
IC 3599	0.13	V-BLR	85 ± 17	[c]	5.11	1.92	-	-
MrK 766	0.63	V-BLR	81 ± 17	[c]	5.79	1.90	41.6	10.62
MrK 896	4.43	V-BLR	87 ± 11	[c]	6.64	1.93	-	-
NGC 4051	1.35	V-BLR	88 ± 13	[c]	6.13	1.94	41.6	10.62 ± 0.1
MrK 202	1.3 ± 0.4	r	78 ± 3	[d]	6.113	1.89	-	-
NGC 3783	29.8 ± 5.4	v	95 ± 10	[e]	7.474	1.97	45.7	10.66 ± 0.1

Reference: [a]- Jian Hu,2008; [b]- F. Ricci,2017; [c]- V. Botte,2004; [d]- C. J. Grier,2021; [e]- Christopher A. Onken,2004

This table has values for galaxies that are described by the method or their study - Stellar Kinematics, Gas Kinematics, Virial Theorem to BLR clouds, Reverberation Mapping and studies of the BLR using Optical Continuum Luminosity. More about these have been mentioned in 3.1.

We further researched the significance of another correlation, namely $M_{Bulge} - M_{BH}$ relation, that helps us in understanding their behaviour with respect to the properties of the galaxies.

3.2 | Methodology

We have selected galaxies that have a stellar velocity dispersion in the region of 40 to 110 km/s. Tabulated the values obtained for central stellar velocity dispersion and their corresponding black hole mass through various methods. Then we tabulated the mass of the bulge of the galaxies and their corresponding black hole masses.

3.2.1 | Sources for Galactic Velocity Dispersion values

We obtained the velocity dispersion of each galaxy from the papers referred to in Table 1. The method used to find the stellar velocity dispersion of each galaxy is clearly defined in the respective papers, cited in section 3.2.2.

3.2.2 | Sources for Mass of the Blackhole

For NGC 221 we got the mass of the black hole through the stellar kinematics method (Jian Hu; The black hole mass–stellar velocity dispersion correlation: bulges versus pseudo-bulges, June 2008)(Hu, 2008), for NGC 4151 we got the mass of the black hole through stellar kinematics method and gas kinematics method(Jian Hu; The black hole mass–stellar velocity dispersion correlation: bulges versus pseudo-bulges, June 2008). Value of mass of the black holes of NGC 7457, NGC 4742, NGC 4486 A calculated through stellar kinematics (Jian Hu; The black hole mass–stellar velocity dispersion correlation: bulges versus pseudo-bulges, June 2008). For NGC 6221, NGC 7465, ESO 234-GO50 value of their black holes calculated through BLR and AGN Optical Continuum Luminosity method (F. Ricci; Detection of faint broad emission lines in type 2 AGNs – III. On the M_{BH}- $\sigma*$ relation of type 2 AGNs, October 2017)(Ricci, 2017b). And MrK 335, UGC 3478, MrK 705, IRAS 766, IC 3599, MrK 766, MrK 896, NGC 4051 mass of the black hole calculated through Virial theorem to BLR cloud method (V. Botte, S. Ciroi, F. Di Mille, P. Rafanelli and A. Romano; Stellar velocity dispersion in narrow-line Seyfert 1 galaxies, 2004 October 12)(Botte, 2004). Using reverberation method (C. J. Grier; Stellar Velocity Dispersion Measurements In High-Luminosity Quasar Hosts And Implications For The AGN Black Hole Mass Scale)(Grier, 2013) and virial theorem(Christopher A. Onken; Supermassive Black Holes in Active Galactic Nuclei. II. Calibration of the Black Hole Mass–Velocity Dispersion Relationship for Active Galactic Nuclei, 2004 May 26)(Onken, 2004) we calculated the mass of the black hole of MrK 202 and NGC 3783.

3.2.3 | Sources for Galactic Bulge Mass

We obtained the values of bulge mass from (F. Ricci; Detection of faint broad emission lines in type 2 AGN: III. On the M_{BH} - $\sigma *$ relation of type 2 AGN(Ricci, 2017a), Wei-Hao Bian and Yong-Heng Zhao 2003(Bian and Zhao, 2003); On the Black Hole – Bulge Mass Ratios in NarrowLine Seyfert I Galaxies). They calculated the bulge mass of these galaxies from the absolute B magnitude of the bulge (M_{Bulge} B) of the host galaxies (Laor 1998; Wandel et al. 1999; Mathur 2000)(Laor, 1998)(Mathur, 2000)(et al, 1999). The equation in Simien & de Vaucouleurs(1986)(de Vaucouleurs, 1986) is used for calculating the mass of the bulge mass from the galaxy's total B bulge magnitude:

$$M_B^{bulge} \equiv M_B^{total} - 0.324\tau + 0.0542\tau^2 - 0.00473\tau^3$$

The bulge luminosity is calculated from the empirical formula :

$$log(L_{bulge}/L_0) \equiv 0.4(-M_V^{bulge} + 4.83).$$

using the relation magnitude

B-V =0.8 where B is the bulge and V is the Keplerian velocity.

The bulge masses of all galaxies in table 2 is calculated using Finally, using the relation between the bulge mass and the bulge luminosity for normal galaxies from Magorrian et al. (1998):

$$log(M_{bulge}/M_0) \equiv 1.18log(L_{bulge}/L_0) - 1.11$$

We studied and plotted the mass of central black holes vs the Stellar velocity dispersions and the Bulge masses vs the masses of the central black holes, as these are the data at the crux of the understood relationship between central supermassive black holes and their host galaxies. The logarithmic values for these values have been taken to make the plot easier to understand.

The data encompassed in the tables has been plotted using Python , resulting in the graphs and findings, discussed in the following section.

4

Results & Inference

4.1 | Log (M_{BH}) vs Log (σ)

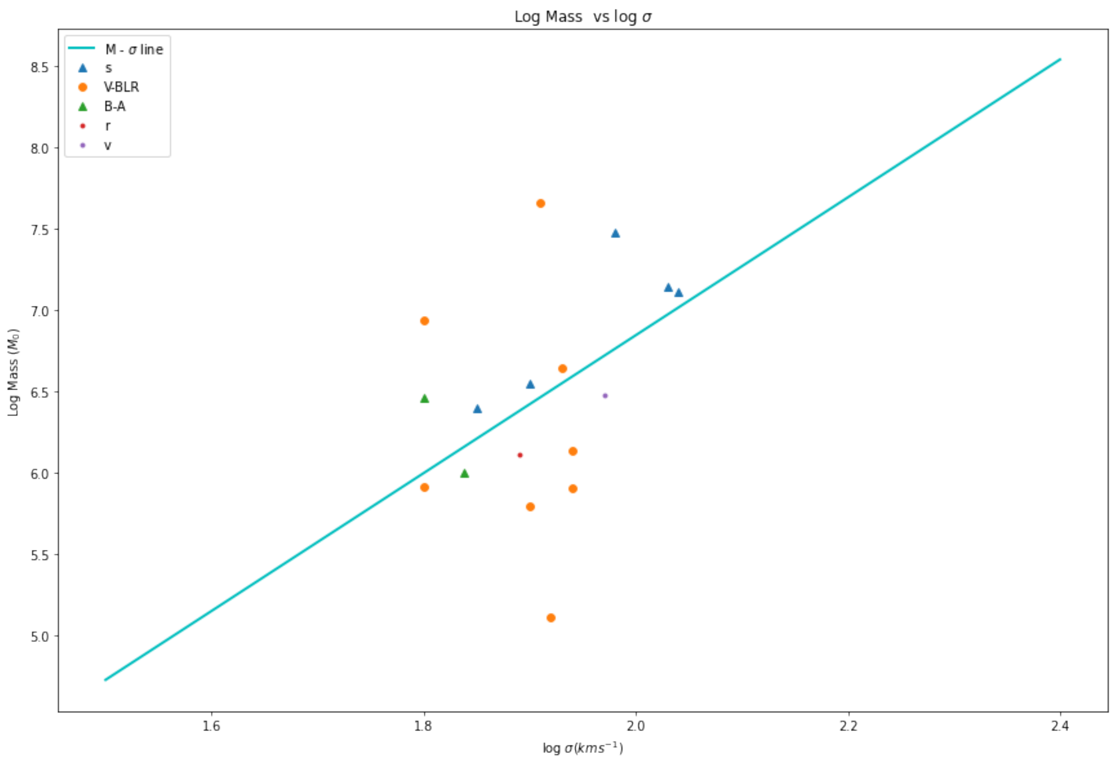

Figure 4.1:

The graph in Figure 4.1 studies the relation between masses of the black hole to their stellar velocity dispersion. On the x-axis, log σ and on the y- axis we took the log mass. It was observed that most of the black holes were scattered near to the M - σ line, but a few studies on the basis of Viral Theorem to BLR clouds were showing large variations. The correlation between M_{BH} and σ was observed to not be as tight as expected, hence leaving us with the thought that whether the M - σ relationship needs further refinement.

4.2 | Log (M_{BH}) vs Log (M_{Bulge})

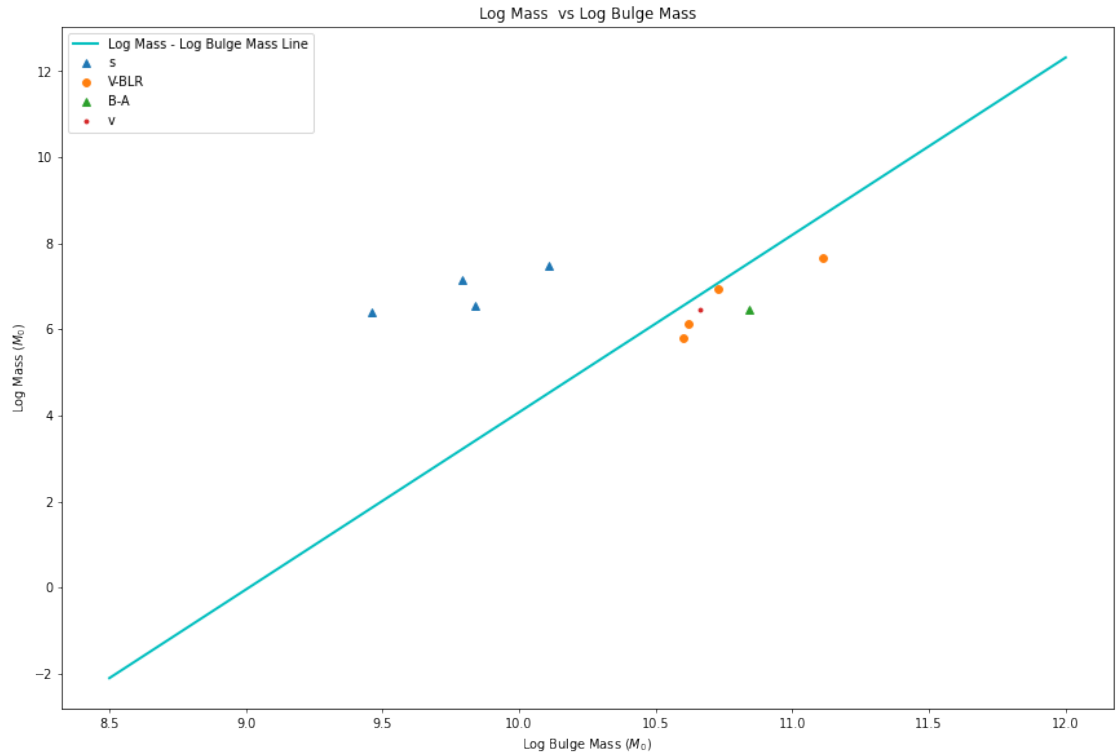

Figure 4.2:

The graph in Figure 4.2 portrays the relation between the masses of the black holes and their bulge masses. On the x-axis, we took log (M_{Bulge}) and on the y - axis we took the log (M_{BH}) . Interestingly, in this plot, we saw that V - BLR clouds were closer to the log (M_{BH}) vs log (M_{Bulge}) line as compared to masses measured by other methods. Thus, it shows that V - BLR black holes tend to follow the relation. But the black holes studied under S (NGC 221, NGC 4151, NGC 4742), B-A (NGC 6221) and V (NGC 3783) are not projecting this trend. These galaxies were scattered in the vicinity of the Log (M_{BH}) -

Log (M_{Bulge}) line. So we could see little to no good correlation between them. However, with a larger study, the spuriousness in the plot might be eliminated.

5

Limitations and Discussion

Ferrarese's M - σ relation in the scientific community and various data has been almost accurately estimated using this relation. The surprising results brought forward by our project might question its reliability and the need for its further refinement. The most probable reason for these discrepancies in the M - σ relation would be the diversity of the dataset that was used for this project. The chosen dataset had a wide range of galaxies and the masses of the black holes tabulated were estimated using various methods like Stellar kinematics, Gas kinematics, Reverberation Mapping, Virial Theorem to BLR Cloud velocity; and BLR of AGN and optical continuum luminosity. Therefore, it had led to difficulty in putting forward a uniform error margin. Nevertheless, the lack of a tighter relation between the mass of the black hole and its galaxy's stellar velocity dispersion is still extremely surprising since the M - σ relation has been thoroughly studied and is well established in the field of astrophysics. The (M_{BH}) -(M_{Bulge}) relation also surprises us here since a slightly tighter correlation is shown through the plot.

6

Future Scope

This is a very interesting topic to be studied in the future and surely an exciting one. From the data collected above, and the correlation we have found later on we could see that for very low-velocity dispersion the M - σ relation was not as tight as expected, thus pegging the thought of whether the M - σ relation needs further refinement.

A

User Manual

Python is the programming language that we have used to plot both the graphs, Log (M_{BH}) vs Log (σ) and Log (M_{BH}) vs Log (M_{Bulge}). We used "math", "numpy" and "matplotlib" python packages to plot the graph from the data. "Math" package was used to obtain the $\log_{10}()$ values of the mass, bulge mass and the σ . "Numpy" was used to store the data in the array, and "matplotlib" was responsible for the final plot in its form. Initially, all the masses and the σ values were stored into two variables and then a correlation line was obtained. We made use of the polyfit() function for this. Now we separately stored the masses and σ values into different variables as classified based on the study of Stellar Kinematics, Gas Kinematics, Virial Theorem to BLR clouds, Reverberation Mapping and took the plot from each category.

log(M/M_0) = (8.12)+(4.24) log (σ / 200) km s^{-1}

This equation was used to obtain the M - σ line under the log() function. Similarly, for Log (M_{BH}) vs Log (M_{Bulge}). Here we used

log(M/ M_{Bulge}) = (8.20)+(4.12) log ($\mathrm{M}_{Bulge}/10^{-11}$) km s^{-1}

to get the Log (M_{BH}) - Log (M_{Bulge}) line.

B

Gallery

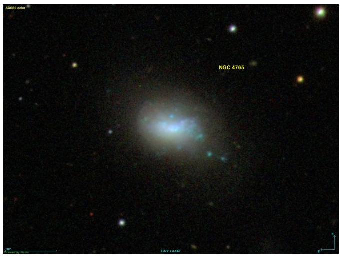

Figure B.1: NGC 4765, Strasbourg Data Center

Figure B.2: NGC 4486A, Hubble Space Telescope

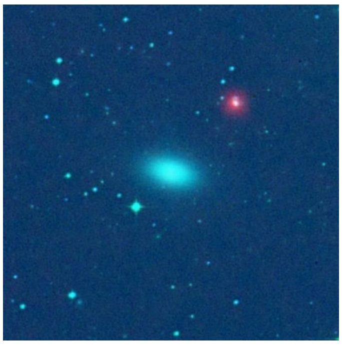

Figure B.3: NGC 4742, Created by Sirswa Kuldeep, Using NASA/SkyView

Figure B.4: NGC 3783, Created by Sirswa Kuldeep, Using NASA/SkyView

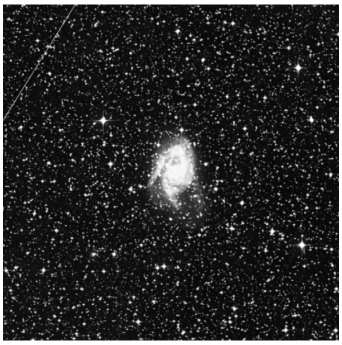

Figure B.5: NGC 6221, Digital Sky Survey

Figure B.6: NGC 4051, NASA/ESA Hubble Space Telescope

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