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A Comparison of Supermassive Black Hole Mass of NGC 4151 Using Different Methods

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ABSTRACT

We found a new value of supermassive black hole (SMBH) mass in the middle of type 1 Seyfert, NGC 4151 galaxy. In this Study, the image of NGC 4151 galaxy was deprojected to face-on, using spiral galaxy of face-on, and applied IRAF to calculate the ellipticity and position angle of major-axis. A two-dimensional (2D) Fast Fourier Transform (FFT) applied to the deprojected image to calculate the spiral arm of NGC 4151 galaxy, and, in that way, find a central mass AGN 4151 galaxy. We compared our results of the mass of SMBH in in the center of NGC 4151 galaxy with the mass of SMBH calculated using different methods ((direct method: stellar dynamics, gas dynamics, reverberation mapping), and indirect method: M_{BH}-σ*, M_{BH}-V_{rot}, M_{BH}-n, M_{BH}-L_{bulge}, and M_{BH}-P correlations). We concluded that the results of mass for these methods are in agreement with the estimated ones, i.e. using direct methods.

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Keywords: SMBH mass– pitch angle - luminosity of the bulge – bulge velocity dispersion - rotational velocity

1. Introduction

Supermassive black holes (SMBHs) are existed at the middle of the galaxies [1, 2]. In addition, their masses are as thousands to billions as the solar masses [3, 4 , 5, 6]. Astrophysics studies have found that there are tight relationships locally for the SMBHs and the components of their hosts [6, 7]. Astrophysicists found that the energy released by increasing BH play great role in shaping the characteristic of the host galaxy [8, 9]. Most bulges of galaxies contain a central SBH that mass relates with dispersion velocity (σ*) (M_{BH}-σ*) ;[2, 10, 11] with luminosity (L_{bul}) (M_{BH}-L_{Bulge}) [1, 3, 12, 13, 14]; with circular or rotation velocity [15], with index of the Sersic [16,17], with pitch angle (P) [18]. In this work, we have selected only AGN 4151 galaxy with trusted M_{BH} estimates (stellar or gas dynamics and masers). These are estimates of SMBH masses using different relations (indirect methods).

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2. Measurement of SMBHs using 2.1 M_{BH}-σ* and M_{BH} − P relations

There are varieties of methods for measuring SMBH masses. In this work, we have selected NGC 4151 galaxy, and two types of relationships for mass measurements. First, we used the relationship for SMBH mass (M_{BH}) and dispersion velocity (σ_*) (M_{BH}-σ_*) [2, 10], then we used the relationship for SMBH (M_{BH}) and pitch angle (P) [18, 20].

2.2 Measurement SMBHs using (M_{BH}- σ_*) relation

The M_{BH}- σ* relationship assists to understand the theory of formation for black hole in the center of galaxy and the dispersion velocity [15, 21]. The M_{BH}– σ* relationship is one of the best methods applied to measure SMBH mass [12]. This technique connects masses of black hole and dispersion velocity [2, 10], because BH masses in spirals galaxies do not have higher masses, the M_{BH}- σ* correlation used to exactly measure SMBH [22, 23]. SMBH masses of classical bulges and pseudo bulges relate with the velocity dispersion (σ*) using the following correlation [11]:

$$M_{BH}(\sigma_*) = 10^{8.13\pm0.06}(\sigma_* /200 \text{ km s}^{-1})^{4.02\pm0.32} \quad (1)$$

Using NGC 4151 spiral galaxy observed at Spitzer of 3.6μm along with the M_{BH}-σ* correlation, the mass of SMBH was measured.

2.3 The Measurement SMBH using pitch angle

There is an important technique to measure mass of SMBH in spiral galaxy using the correlation for SMBH at the center of spiral galaxy with the spiral arm (P) [18, 20]. SMBH masses are correlated by a good relation with Pitch angle. In addition, a relationship between spiral arm (P) and shear of rotation curve (S) was proved [24, 25].
Most of previous studies showed the descriptive logarithmic spiral in polar coordinates [26, 27, 28, 29, 30, 31]. This is a specific type of the curve of spiral that shows the characterization of the spiral arm of the galaxy:

$$r = r_0\, e^{\theta \tan(\varphi)} \qquad (2)$$

Where: r: radius, θ: central angle, r_0 is initial value at θ = 0, and spiral arm angles are between (-90 and 90).

Pitch angles spiral arm estimated using a decomposition of 2-dimension (2DFFT) for logarithmic spiral of NGC 4151 galaxy, with inclination angle was 33°. Each component of amplitude of Fourier is given by [31]:

$$A(m,p) = \frac{\sum_{i=1}^{I}\sum_{j}^{J} I_{ij}(\ln r,\theta)\exp[-i(m\theta + p * \ln r)]}{\sum_{i=1}^{I}\sum_{j=}^{J} I_{ij}\,(\ln r,\theta)} \qquad (3)$$

Where:

r , θ represented the polar coordinates,

I(ln r, θ): the intensity at coordinates (ln r, θ),

m: the arms number,

p: the related with the spiral arm (P) by P =−(m/pmax).

IRAF applied to measure the ellipticity value and angle of the position in order to deproject the images of NGC 4151galaxy to fully face-on. Using ELLIPSE to derive inclination angle (α) [32, 33], which is defined by:

$$\alpha = \cos^{-1}(b/a) \qquad (4)$$

Where: the value 0° is (face-on galaxy) and 90° is (edge-on galaxy).

Assuming logarithmic spirals, the spiral arm were calculated by applying the relationship between masses of SMBH and (P) [18]. The $M_{BH} - P$ correlation is fit using a model of the double-power-law:

$$M_{BH} = 2^{(\beta-\gamma/\alpha)} M_{BHb}\,(P_b/\,P)^{\gamma}\,[1+(P/P_b)^{\alpha}\,]^{\,(\gamma-\beta/\alpha)} \qquad (5)$$

The SMBH mass was estimated with values of parameters provided by: β = 126.1, γ = 2.92, Pb =40.8°, α = 23.5, and M_{BHb} = 1.72 × 10^4 M_Θ [18].

2.4 Measurement of the bulge luminosity (L_{bulge})

The bulge luminosity measurement is based on a 2D decomposition (bulge - bar - disk) for image (AGN 14151 galaxy) of model Laurikainen 2005. The luminosity of bulge is measured of NGC 4151 galaxy by using the two-dimensional multicomponent decomposition technique. In this technique, a function was applied on the disc:

$$I_d(r) = I_{od} \exp[-(r/h_r)] \qquad (6)$$

Where I_{od} is the center density of the disc, h_r is the radial of disc scale length, and r is disc radius. Below is the description of the bulge using a Sersic function:

$$I_b(r_b) = I_{0b} \exp\left[-(r_b/h_b)^{\beta}\right] \qquad (7)$$

Where I_{ob} is the center of surface density in the (bulge), h_b is the bulge scale parameter, and β=1/n with n= index of sérsic parameter. The half-light radius (effective radius), r_e, of the bulge using converting h_b,

$$r_e = (b_n)^n\, h_b \qquad (8)$$

Where the value of b_n is Γ(2n) = 2γ(2n,b_n). Γ and γ are the complete and functions of incomplete gamma, respectively. We use: $b_n \approx 2.17 n_b - 0.355$; [35], and n_b is the Sersic index of bulge.
The bar of spiral galaxy is measured using a Sersic function:

$$I_{bar}(r_{bar}) = I_{0bar}(1-(r_{bar}/a_{bar})^2)^{n_{bar}+0.5},\ r_{bar} < a_{bar}$$
$$= 0\ , \qquad\qquad , r_{bar} > a_{bar}$$
(9)

Where I_{0bar} is the center of surface brightness of the b_{ar}, a_{bar} is the bar major axis, and n_{bar} is the exponent of the bar model [34].
Using SExtractor, other sources were masked out [33, 34, 36]. To transfer units of surface brightness to mag arcsec-2, using the following formula:

$$\mu_{3.6\mu m} = -2.5 \times \log_{10}\left[\frac{S_{3.6\mu m} \times 2.35\times10^{-5}}{ZP_{3.6\mu m}}\right] \qquad (10)$$

The resultant 3.6 μm magnitude of AGN 4151 is listed in Table (1) Absolute 3.6 μm magnitudes were calculated using the standard relation:

$$M_{3.6\mu m} = m_{3.5\mu m} - 5 \log d + 5, \quad (11)$$

Where (d) is the luminosity distance in parsecs. The luminosity of the bulge was estimated using this relation:

$$\log (L_{3.6\mu m}/L_{\Theta}) = 0.4(-M_{3.6\mu m} + 3.24) \quad (12)$$

Thus, SMBH of AGN 4151 galaxy estimated using the relation between SMBH masses (M_{BH}) and bulge luminosity [38]:

$$\log M_{BH}/M_{\Theta} = (8.19 \pm 0.06) + (0.93 \pm 0.10) \times [\log(L_{3.6,bul}/L_{3.6,\Theta}) - 11] \quad (13)$$

2.5 The maximum velocity of rotation and SMBH Mass

The maximum velocity of rotation is found from the HI 21-cm line width, and was taken from the astronomical literature and datacenters (HyperLeda). This rotation velocity has been corrected for inclination determined from the apparent flattening of spiral galaxies. The inclination of NGC 4151 galaxy has been estimated using the axis ratio α = arcos (b/a) [39][40][41], the rotational velocity of the gas (which represents the maximum rotational velocity, expressed in km/s.).

SMBH mass are measured by applying the correlation between SMBH and V_{rot} discover by Bases et al. (2004) [42]. The $M_{BH} - V_{rot}$ relation is fit by Bases et al.:

$$\log(M_{BH}/M_{\odot}) = (4.21\pm0.60)\log(V/V_0) + (7.24\pm0.17) \quad (14)$$

Where V_0= 200 km s^{-1}

2.6 Sersic index and SMBH mass

The Sersic index was measured using IRAF routine Ellipse [33]. Graham et al. (2007) discovered a strong relationship between Sersic index and supermassive black hole mass. The form of this relationship is:

$$\log(M_{bh}/M_{\odot}) = (7.98 \pm 0.09) + (3.70 \pm 0.46)\log(n/3) - (3.10 \pm 0.84)[\log(n/3)]^2 \quad (15)$$

The Sersic index is measured by applying the bar - bulge - disk decompositions of image of galactic bulge of AGN 4151 galaxy. Thus, the relationship between SMBH and Sersic index (n) is discovered by Graham et al. (2007) provides an estimate of SMBH masses [16].

3. Results and Discussion

In Table (1), the results are presented. Equations (1), (2), (3), (4), and (5) were used to measure the SMBH, which are in Col. (9). By the $M_{BH} - \sigma*$, $M_{BH} - P$, $M_{BH} - L_{bulge}$, $M_{BH} - V$, and M_{BH}-n relations, equations (1), (2), (3), (4) and (5) were used to measure the SMBH masses from the dispersion velocity (σ∗), spiral arm pitch angle (P), bulge luminosity (L_{bulge}), rotation velocity (V_{rot}), and Sérsic index (n), which are listed in Col. (9). In addition, SMBH masses listed in col. (9) were taken from the literature, which were measured using reverberation mapping (RM), stellar/gas dynamics (S/G) techniques.

The SMBH mass estimates were determined using the direct methods (RM and S/G) and indirect methods $M_{BH} - \sigma*$, $M_{BH} - P$, $M_{BH} - L_{bulge}$, and M_{BH}-n relations are moderately consistent, within 1σ of each other.

Fig. 1 explains surface brightness profiles of the NGC 4151 galaxy are separated for each part in the model. Two kind of brightness profile are explained. From Fig. 1, the model obtained is a good representation to study the galactic components, especially, bulge luminosity component, that were used to calculate SMBH mass using Equations (3).

Indeed, the $M_{BH} - L_{3.6\mu m}$ relation is the tightest correlation that we used to find the SMBH mass of AGN 4151galaxy; its result is often consistent with the results of direct methods like reverberation mapping [43] and stellar and gas dynamics [44]. The results are shown in Fig. 2, the results are deduced using the M_{BH}–L_{bul}, M_{BH}–n, M_{BH}-V_{rot} and M_{BH}–σ_* relationships, RM, and S/G respectively.

The results we have reached to are analyzed and compared using M_{BH}-P relation [18] in Fig.2 to provide a consistent comparison with results of above relations in terms of the SMBH masses. As described below, the results of six techniques provide consistent results for the M_{BH}–P relation. The results are shown in Fig. 2, where we present the results ($\log M_{BH}/M_{\odot}$ = 7.529±0.38, 7.923±0.52, 7.696±0.47, 5.501 ±0.35, 7.64±0.11, and 7.66±0.05) using the M_{BH}–L_{bul}, M_{BH}–n , M_{BH}–σ_*, M_{BH}-V_{rot} , relations, RM and S/G methods respectively.

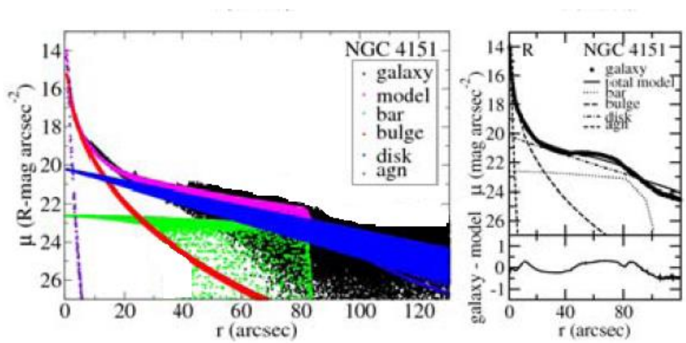

Figure 1: illustrate the results of decomposition of image for NGC 4151 galaxy.

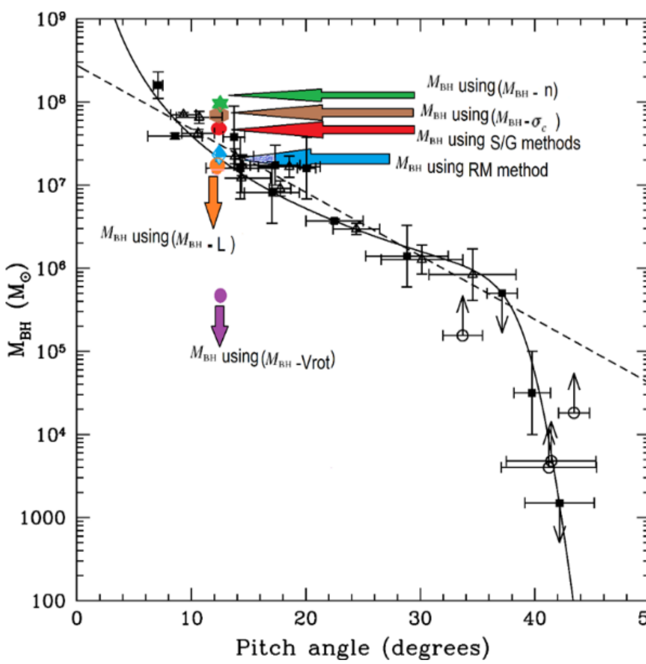

Figure 2 :we compare supermassive black hole mass measurements from Seigar (2008) to the measurements from this study. Supermassive black hole masses in this study are taken using different methods.

From Fig.2, the results, point out that the M_{BH} mass using M_{BH}-V_{rot} relation is outliers and significantly below the linear regression of M_{BH}-P relation.

The results of six methods provide consistent results for the M_{BH}–σ_* relation [11]. The results are shown in Fig. 3, where we present the results of ($\log M_{BH}/M_{\odot}$ = 7.529±0.38, 7.923±0.52, 7.49±0.24, 5.501±0.35, 7.64±0.11, and 7.49±0.24) using the M_{BH}–L_{bul}, M_{BH}–n , M_{BH}–P , M_{BH}-V_{rot} relations, RM and S/G methods respectively.

From Fig. 3, we found that the M_{BH} mass using M_{BH}-V_{rot} relation is outliers and significantly below the linear regression of M_{BH}-σ_* relation.

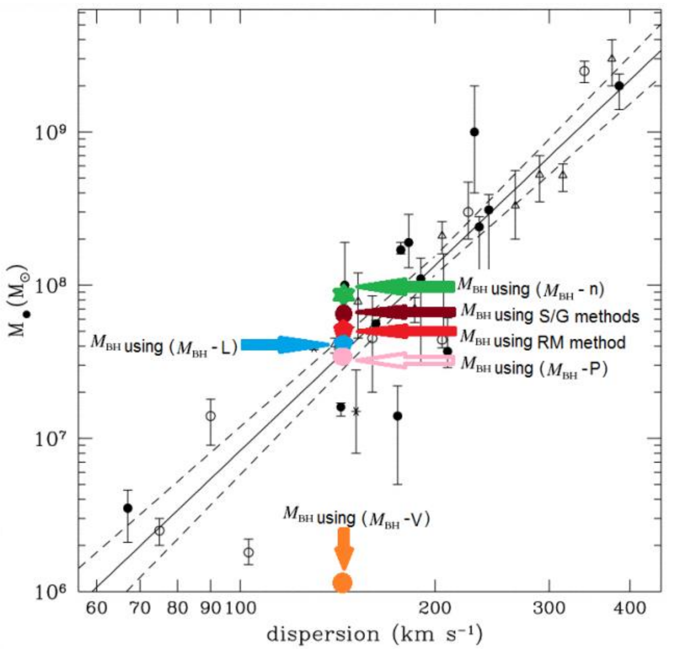

Figure 3: A comparison of supermassive black hole mass measurements from Tremaine et al. (2002) [11] to the measurements from this study. Supermassive black hole masses in this study are taken using different methods.

These results using different techniques provide consistent results for the M_{BH}–P relation. The results are shown in Fig. 4, where we present the results (logM_{BH}/$M_\odot$ = .49±0.24, 7.923±0.52, 7.696±0.47, 5.501±0.35, 7.64±0.11, and 7.66±0.05) using the M_{BH}–P, M_{BH}–n, M_{BH}–σ_*, M_{BH}- V_{rot} relations, RM and S/G methods respectively.

Fig. 4, the results of the M_{BH} mass using M_{BH}-V_{rot} relation is outliers and significantly below the linear regression of M_{BH}-$L_{3.6\mu m}$ relation.

This result (M_{BH} using M_{BH}-V_{rot}) confirms the non- existence of a relation for SMBH and the dark matter halos which is represented by the rotation velocity (V_{rot}).

As mentioned above, the results shown in this figures 2, 3, and 4 confirm the results presented by Kormendy (2011), indicating that found the Supermassive black holes do not relate with dark matter halos of galaxy [45].

Not surprisingly, the rotation velocity is not intimately related to SMBH mass, although some researchers argued that a relation for M_{BH} and V_{rot} must be reflected in an M_{BH} – V_{rot} relation, where V_{rot} is the rotation velocity [15].

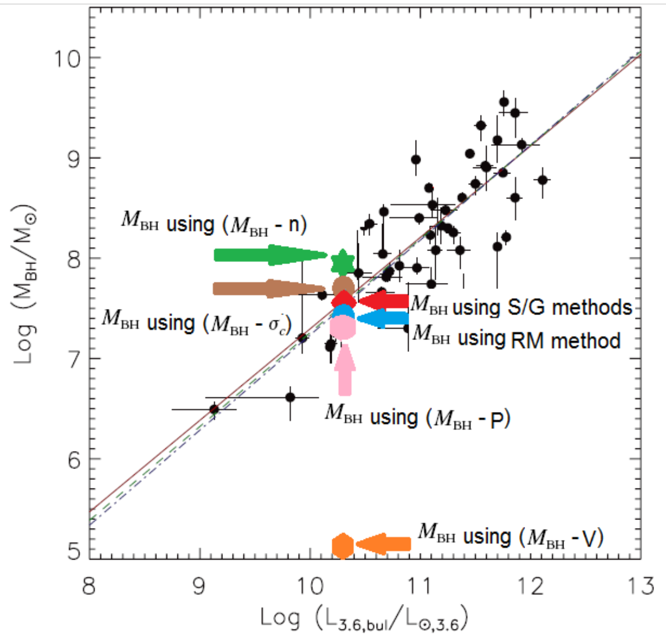

Figure 4: Illustrate a comparison between BH mass measurements from Sani (2011) [38] and the measurements from this study. The BH masses in this study are taken using different methods.

Table 1: Columns are as follow: (1) distance in Mpc[38]; (2) dispersion velocity in km s−1 [38]; (3) spiral arm pitch angle; (4) rotation velocity in km s-1 taken from HyperLeda catalogue; (5) Sérsic index; (6) 3.6μm magnitude; (7) 3.6μm Absolute magnitude; (8)

Dist. (1) (Mpc)	σ_* (2) Km s^{-1}	P (3) (degree)	V_{rot} (4) Km s^{-1}	n (5)	$m_{3.6\mu m}$ (6)	$M_{3.6\mu m}$ (7)	log $L_{3.6\mu m,\odot}$ (8)	logM_{BH}/$M_\odot$ (9)	Method (10)
								7.64±0.11 [43]	RM
								7.66±0.05 [44]	S/G
		12.4±1.3						7.49±0.24	M_{BH}-P
20					9.02±0.04	22.42±0.03	10.29±0.02	7.529±0.38	M_{BH}-$L_{3.6\mu m}$
	156±8							7.696±0.47	M_{BH}-σ_*
			77.3±1.7					5.501±0.35	M_{BH}-V_{rot}
				3.2				7.923±0.52	M_{BH}-n

4. Conclusion

The SMBH mass estimates are determined using direct methods (RM and S/G) and indirect methods $M_{BH} - \sigma*$, $M_{BH} - P$, $M_{BH} - L_{bulge}$, $M_{BH} - V$, and M_{BH}-n relations are moderately consistent, within 1σ of each other.

Our results of AGN 4151 using indirect methods are consistent with the result of direct methods (RM and S/G), except the result of M_{BH} is obtained by using the M-V is significantly below the linear regression of M_{BH}−P relation on the diagram of M_{BH}-P. This is consistent with the agreement between SMBH masses (using RM, S/G) and those determined from using (M_{BH}-σ*, M_{BH}-n, M_{BH}-L_{bulge}, and M_{BH}-P) that we found in our study. This means that the M_{BH} masses for five methods and the M_{BH}-P, are fairly consistent with each other.

Conflict of interest

None.

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