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A Study of the Relation between the Spiral Arm Pitch Angle and the Kinetic Energy of Random Motions of the Host Spiral Galaxies

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Running Title: A Relation between Pitch Angle and Kinetic Energy in Spiral Galaxies

Abstract

In this work, we report a relation between the kinetic energy of random motions of the corresponding host galaxies and spiral arm pitch angles ($M_{dyn}\sigma^2$ - P), ($M_*\sigma^2$ - P) where M_{dyn} is the bulge dynamical mass, M_* is bulge stellar mass, and σ is the velocity dispersion of the host galaxy bulge. We measured the spiral arm pitch angle (P) for a sample of Spitzer/IRAC 3.6-μm images of 54 spiral galaxies, estimated by using a 2D Fast Fourier Transform decomposition technique (2DFFT). We selected a sample of nearly face-on spiral galaxies and used IRAF ellipse to determine the ellipticity and major-axis position angle in order to deproject the images to face-on, and using a 2D Fast Fourier Transform decomposition technique, we determined the spiral arm pitch angles. We estimated the kinetic energy of random motions of the corresponding host galaxies ($M_{dyn}\sigma^2$, $M_*\sigma^2$) by using M_{dyn}, M_*, and σ, where the stellar velocity dispersion (σ) of the bulge was taken from the literature. We determined the bulge dynamical mass (M_{dyn}) using the virial theorem, and the bulge stellar mass (M_*) was estimated by using the bulge 3.6-μm luminosity with the appropriate stellar mass-to-light ratio (M/L).

Introduction

It is becoming apparent that the energy output from supermassive black holes (BH) at galaxy centers plays a important role within the formation and evolution of galaxies (Pastorini et al. 2007). Over the past 15 years, one of the most important advances and the most fascinating discoveries was that galaxies typically contain supermassive black holes at their centers, on the order of millions to billions of solar masses (Heckman and Kauffmann 2011).

SMBH mass is an important parameter for us to understand nuclear energy mechanics and the formation and evolution of SMBHs and their host galaxies (Rees 1984, Tremaine et al. 2002). Nowadays astrophysicists believe that the energy released by growing SMBHs plays an important role in shaping the properties of the structure of galaxies (Benson and Bower 2010, Fabian 2012). The co-evolution of galaxies and SMBHs is now widely accepted although many details on how this coexistence works are still understudied (Heckman et al. 2004). Therefore, we cannot understand how galaxies formed and evolved without understanding the co-evolution of galaxies and SMBHs.

In light of the increasing evidence derived from scientific research that indicates that the mass of SMBHs are tightly related to the properties of their host galaxy bulges, it seems obvious that SMBHs play an important role in galaxy formation.

Most galaxy bulges contain a central supermassive black hole whose mass strongly correlates with stellar velocity dispersion (σ^*) within the effective radius (r_e) (Ferrarese and Merritt 2000, Gebhardt et al. 2000, Tremaine et al. 2002) with the bulge luminosity or spheroid luminosity of the galaxy (L_{bul}) (Kormendy and Richstone 1995, Magorrian et al. 1998, Marconi & Hunt 2003, Häring and Rix 2004, Gültekin et al. 2009), with the bulge mass (M_{bulge}) (Magorrian et al. 1998, MH03, Häring and Rix 2004, hereafter HR04), and circular velocity (Ferrarese 2002), with the galaxy light concentration (Graham et al. 2001), the dark matter halo (Ferrarese 2002), with the effective radius (Marconi and Hunt 2003), the Sersic index (Graham and Driver 2007), with the gravitational binding energy and gravitational potential (Aller and Richstone 2007), combination of bulge velocity dispersion, effective radius and/or intensity (Aller and Richstone 2007), with the radio core length (Cao and Jiang 2002), and the inner core radius (Lauer et al. 2007a). Using more sophisticated techniques of measuring the bulge luminosity or dynamical modeling of the host galaxy such as two-dimensional image decompositions (e.g., McLure and Dunlop 2001, Wandel 2002, Hüring and Rix 2004, Hu 2009, Sani et al. 2011), produces a tighter correlation between SMBHs and the host galaxy.

The results of Hopkins et al. (2007) and Marulli et al. (2008) provide evidence for a hypothesis that bulge of galaxy and SMBHs do not form and evolve independently. Furthermore, Feoli and Mancini (2009) explained the relation M_{bul}- σ^2 by using a plausible physical interpretation that resembles the H–R diagram, where they indicate that certain properties of SMBHs at the centers of galaxies, such as entropy, can increase with time or at most remain the same, but do not decrease. Therefore M_{BH} depends on the age of the galaxy.

Several previous studies have tested the M_{BH}–$M_{bul}\sigma_2$ relation using several independent galaxy samples, with clear positive results, and therefore the M_{BH}–$M_{bul}\sigma2$ relation can be used as an indirect measurement of the SMBH mass in the center of galaxies (Feoli and Mele 2005,2007, Feoli and Mancini 2009, Mancini and Feoli 2012).

Previous work has found that central SMBH mass is strongly related with spiral arm pitch angle of its host galaxy (Seigar et al. 2008, Davis et al. 2012, Berrier et al. 2013). Pitch angle is the angle between a line tangent to the arm in a spiral galaxy at a given radius and a line tangent to a circle at the same radius. The degree of twist of the spiral arms is a characterization of the pitch angle, where the galaxies with small and large pitch angles have tightly wound spiral arms and open arms respectively (Kennicutt 1981, Ma 2001, Savchenko and Reshetnikov 2011). The measurement of spiral arm pitch angle gives a measure of how tightly the spiral arms of a galaxy are wound. Since the creation of a morphological classification scheme of galaxies by Hubble (1926), authors have competed to investigate the wide correlation of the spiral and morphological type of the observed galaxies (e.g., Kennicutt 1981).

Seigar et al. (2006) and Davis et al. (2012) concluded that pitch angle does not depend measurably on the waveband of the image. Instead, they found consistency between pitch angles of the same galaxy measured both in the B-band and in a near-IR waveband by using a 2D fast Fourier transform (2DFFT) analysis and assuming logarithmic spirals.

The objective of this work is to analyze the cited scaling relationships that involve bulge properties (M_{BH} –$M_{bul}\sigma^2$, M_{BH} –M_{bul}, $M_{bul}\sigma^2$– P and M_{bul}– P) in images of 41 spiral galaxies observed using the Spitzer Space Telescope at 3.6-µm.

Materials and Methods

Sample

Our sample in this research consists of a total of 41 spiral galaxies observed with the Spitzer Space Telescope at 3.6µm. The main requirement to estimate the kinetic energy of random motions of the corresponding host galaxies ($M_d\sigma^2$ & $M_*\sigma^2$) is an estimate of the bulge mass and the stellar velocity dispersion. We have measured both the bulge dynamical mass and the bulge stellar by applying the isothermal model (Hu 2009, Sani et al. 2011) and the calibration by Oh et al. (2008) respectively. The central velocity dispersion of the galaxy hosts were obtained from the literature (see Table 1 at the end of this manuscript).

Our sample consists of Hubble types ranging from Sa to Sc for which it is possible to measure pitch angle for each galaxy. We derived an inclination (ranging from 25 to 65 degrees) by using ellipticity values of the outer 3.6-µm isophotes, which were determined with ELLIPSE in IRAF[1]. Seigar et al. (2005, 2008) noted that the largest source of error in estimating P presumably comes from this determination of radial range, although P can also have a variance as large as 10% for galaxies with large inclinations (>60°) (Block et al. 1999)

In this paper, some of the galaxies had spiral arm pitch angles which had been previously determined by our research group using B- and K- band images (Seigar et al 2006, Davis et al 2012). The remaining spiral arm pitch angles were measured using Spitzer/IRAC 3.6-µm images of 41 galaxies using a two-dimensional fast Fourier transformation (Schröder et al. 1994), assuming logarithmic spirals. In this study, we have considered a consistent sample of 41 spiral galaxies, which consists of 27 barred galaxies, 14 non-barred galaxies, 31 AGN-host galaxies, 10 non-AGN galaxies, 10 galaxies with classical bulges, and 31 galaxies with pseudo-bulges.

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[1] [1]IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Associated Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Measurement of the dynamical bulge mass:

The bulge dynamical mass M_{dyn} is estimated using the virial theorem, i.e., the virial bulge mass (Hu 2009, Marconi and Hunt 2003, Sani et al. 2011) given by:

$$M_{dyn} = kR_e\sigma^2/G \ldots\ldots\ldots\ldots(1)$$

Where k is in general a function of the Sérsic index n (Sani et al. 2011, Jun and Im 2008), we follow the method of Cappellari et al (2006) and use k=5 and this can then be used to estimate an accurate value of M_{dyn}, where σ, and R_e are the host-galaxy bulge velocity dispersion and the bulge effective radius respectively, and G is the gravitational constant.

Measurement the stellar mass (M_*) from the 3.6 μm M/L ratio:

Bell and de Jong (2001) estimated the stellar mass-to-light (M/L or γ) ratio of disk galaxies by using relation between optical colors (e.g., B−R, B−V) and the near-infrared

Previous studies of optical colors of the disk of galaxies do not provide the γ values for the Spitzer/IRAC bands, so we cannot use them here. Therefore we will use a new relation to obtain γ in the 3.6-μm Spitzer/IRAC. This relationship is between γ^K and γ in the 3.6-μm waveband was reported by Oh et al. (2008):

$$\gamma^{3.6} = B^{3.6} \times \gamma^K + A^{3.6} \ldots\ldots\ldots(2)$$

Where $A^{3.6} = -0.05$ and $B^{3.6} = 0.92$

And a relation between the (γK) and optical colors:

$$\log_{10}(\gamma^K) = b^K \times \text{Optical Color} + a^K ..(3)$$

Where a^K and b^K are coefficients for the relation between γ^K and optical colors given in Bell and de Jong (2001).

By combining Equation (2) with Equation (3), adopting 20% solar metallicity (Miller and Hodge 1996), optical colors given in Bell and de Jong (2001) and a scaled Salpeter IMF[2] cutting off the stars less massive than $\sim 0.35M_{\odot}$ (Bell and de Jong 2001), we calculated the 3.6 μm M/L ratio.

Measurement the bulge luminosity (L_{bulge}):

The method to measure the bulge luminosity in this work is based on a two-dimensional (bulge - bar - disk) decomposition program (Laurikainen et al 2005), which we used to decompose Spitzer/IRAC 3.6-μm images of spiral galaxies into a bulge and disk model. From the resulting bulge model, we determined bulge luminosity at 3.6-μm for the sample of 41 spiral galaxies. In this method, we used an exponential function to describe the disk:

$$Id(r) = I_{od}\exp[-(r/h_r)],$$

Where I_{od} is the central surface density of the disk, h_r is the exponential scalength of the disk, and r is distance from the galaxy center. The bulge is described by a Sersic function:

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

Where I_{ob} is the central surface density of the bulge, h_b is the scale parameter of the bulge, and β=1/n. The half-light radius (effective radius), r_e, of the bulge is obtained by converting h_b,

$$r_e = (b_n)^n h_b$$

Where the value of b_n is a proportionality constant defined such that $\Gamma(2n) = 2\gamma(2n,b_n)$. Γ and γ are the complete and incomplete gamma functions, respectively. We use the approximation $b_n \approx 2.17n_b - 0.355$ (Fisher and Drory 2010).

The bars and ovals (when present) are estimated by using a Ferrers or a Sersic function:

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

$$I_{bar}(r_{bar}) = 0 \qquad , r_{bar} > a_{bar}$$

Where I_{0bar} is the central surface brightness of the b_{ar}, a_{bar} is the bar major axis, and n_{bar} is the exponent of the bar model defining the shape of the bar radial profile.

The orientation parameters were estimated using Spitzer/IRAC 3.6-μm images of 53 galaxies with M_{BH} estimates. These images were used to measure the minor-to-major axis ratio (q = b/a), effective radii (Re), the radial profiles of the isophotal major-axis position angles (φ), and the estimated inclinations of the disk using the mean values in the outer parts of the disks (Laurikainen et al. 2005). We first removed foreground stars and masked out all point sources from the Spitzer

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[2] The initial stellar mass function

3.6-µm images by using SExtractor (Bertin and Arnouts 1996), then the surface brightness profiles were derived using the ELLIPSE routine in IRAF (Jedrzejewski 1987, Laurikainen et al. 2005).

Results and Discussion

Table 1 (see end of manuscript) lists the bulge stellar mass, spiral arm pitch angle, the SMBH masses, bulge dynamical mass, bulge stellar mass, and the kinetic energy of random motions of the dynamical and stellar bulge respectively.

From the virial theorem and the stellar mass-to-light ratios, we derived the dynamical bulge mass and stellar bulge mass respectively. Also, from the flux density, we have determined model-based bulge luminosities. Absolute magnitudes were calculated from apparent magnitudes using the distance moduli, and known redshifts.

In this paper, the relations that we studied can be written in the following forms:

$$\log_{10} M_{BH} = b + m\log_{10} x \qquad (5)$$

$$\log_{10} M_{bul}\sigma^2 = b + m\log_{10} x \qquad (6)$$

$$\log_{10} M_{bul} = b + m\log_{10} x \qquad (7)$$

Where b and m are the intercept and the slope of the relation, x is a parameter of the bulge or spiral arm pitch angle.

Equations (5, 6, 7) can be used to predict the values of M_{BH}, $M_{bul}\sigma^2$, M_{bul} in other galaxies once we know the value of x. We have to perform an ordinary linear regression of M_{BH}, $M_{bul}\sigma^2$, M_{bul}, on x for the considered galaxies, for which we already know both the quantities.

Figures 1 and 2 show the SMBH masses as a function of $M_{dyn}\sigma^2$ and $M_*\sigma^2$, for 41 galaxies respectively. We found that the Pearson's linear correlation coefficients for a correlation between M_{BH}-$M_{dyn}\sigma_2$ and M_{BH}-$M_*\sigma^2$ relationship are 0.79, and 0.80 respectively, whereas the slopes of these relationships are 0.59, and 0.58 respectively. Thus, there is no significant difference between the M_{BH}-$M_{bul}\sigma^2$ relation and the M_{BH}-$M_{bul}\sigma^2$ relation.

The fitting results of M_{BH}-$M_{bul}\sigma^2$ correlations are presented in Table 3. Our work in this part, has confirmed the results of Feoli and Mele (2005,2007), Feoli and Mancini (2009), and Mancini and Feoli (2012) who also suggested the existence of a strong relationship between the masses of the SMBHs and the kinetic energy of random motions of its host spiral galaxies.

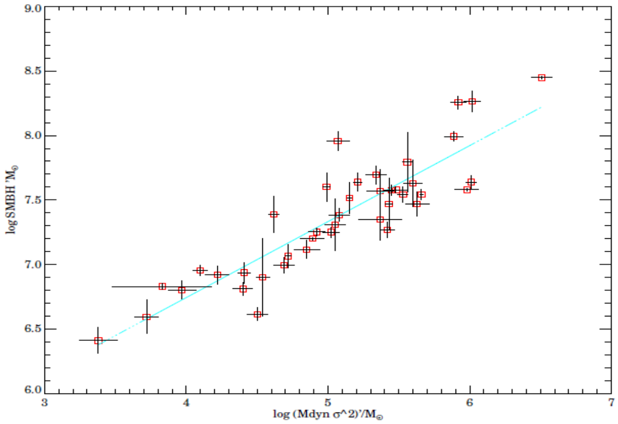

Figure 1. SMBH masses from (M_{BH}-σ) relation as a function of the $M_{dyn}\sigma^2$. The cyan solid line is the fit to all spiral galaxies.

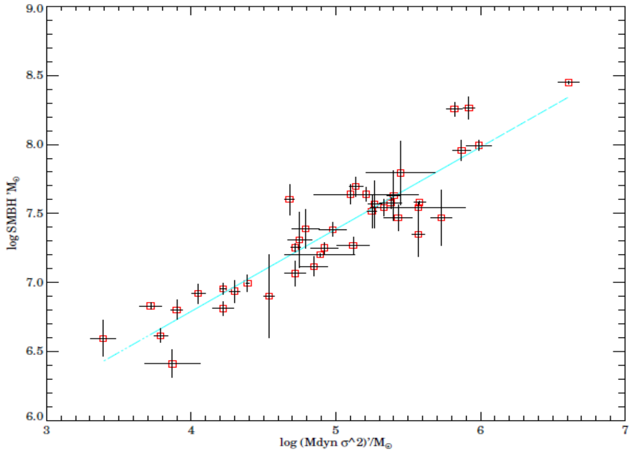

Figure 2. SMBH masses from (M_{BH}-σ) relation as a function of the $M_s\sigma^2$. The cyan solid line is the fit to all spiral galaxies.

Figure 3 presents the M_{BH}-P relation, where P is obtained by using a 2D Fast Fourier Transform decomposition technique (2DFFT). Using the M_{BH}-P relation to study SMBH masses, we can be fairly confident that for galaxies with bulges the pitch angle of the spiral arms should correlate well to the SMBH mass at center of the galaxies. The fitting result of M_{BH}-P correlation is presented in Table 3.

This relation is consistent with that presented in Seigar et al. (2008) and virtually identical in slope:

$$\text{Log}_{10} M_{BH}=(8.44 \pm 0.1) - (0.07 \pm 0.005)\ P$$

We also compared our results with the previous work. Our correlation is consistent with that given by

Seigar et al (2008) for 41 spiral galaxies, but is larger than Berrier et al. (2013). It may be reflective of differences in the data used by Seigar et al. (2008) and Berrier et al. (2013). However, our results confirm the existence of a relationship between spiral arm pitch angle and SMBH mass as originally presented by Seigar et al. (2008) and Berrier et al. (2013).

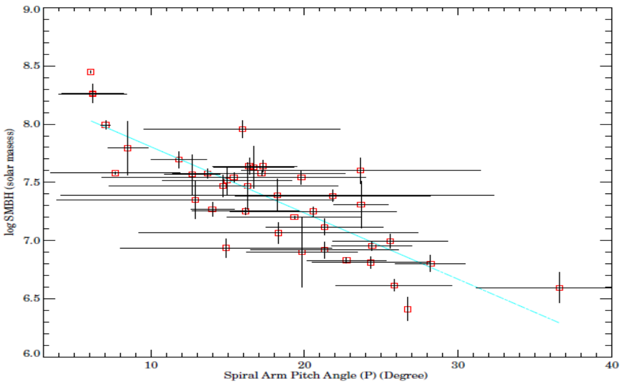

Figure 3. The SMBH mass from (M_{BH}-σ) relation as a function of the pitch angle of spiral arm (P). The cyan solid line is the fit to all spiral galaxies.

Figures 4 and 5 show the SMBH masses as a function of M_{dyn} and M_s for all of our spiral galaxy bulges, where the masses were obtained by using equations (1) and (2). The fitting results of M_{BH}-M_{bul} correlations are presented in Table 3.

From Figures 4 and 5, we can draw two conclusions: the best fitting line for M_{BH} - M_s and M_{BH} - M_d relations, which are shown in Tables 2 and 3. In these figures, containing data on galaxies with both classical bulges and pseudo-bulges, we note that galaxies with both types of bulges follow independent relations although some of the galaxies do harbor an intermediate bulge type, located between the relations of two type of bulge, and this reflects the mixed nature of their bulge properties. The different black hole-bulge relations obeyed by the two types of bulge are emphasized in Figures 4 and 5.

We found Pearson's linear correlation coefficients for a correlation between SMBH and M_{dyn}, M_* are 0.79, and 0.80 respectively, whereas the slope of the M_{BH} - M_d and M_{BH} − M_s relation are 0.76 and 1.01 respectively, which means there is a slight difference between values from both relations, because the difference in M_*/M_d ratio may be related to the mass contribution from the dark matter (Lauer et al. 2007b). In this work, we assumed that dynamical mass of bulges is dominated by the stellar mass, with a negligible contribution of dark matter and gas (Drory et al. 2004, Padmanabhan et al. 2004).

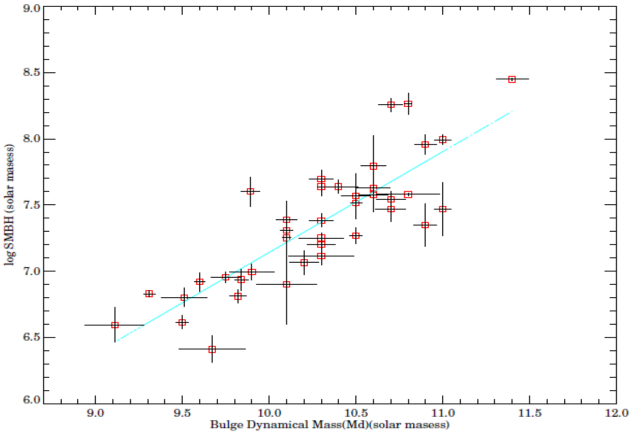

Figure 4. The SMBH mass from (M_{BH}-σ) relation as a function of the bulge dynamical mass. The cyan solid line is the fit to all spiral galaxies.

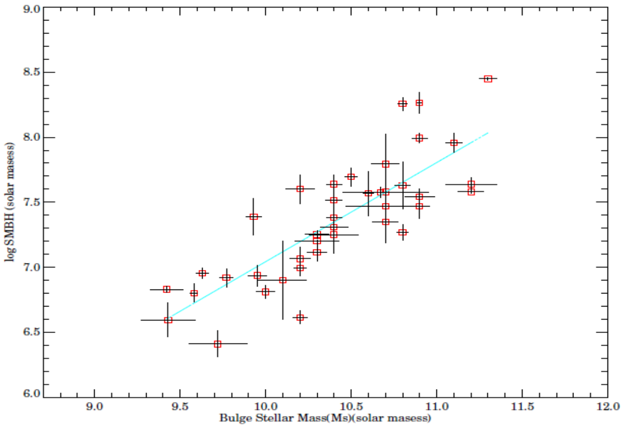

Figure 5. The SMBH mass from (M_{BH}-σ) relation as a function of the bulge stellar mass. The solid line is the fit to all spiral galaxies.

The fitting results are plotted in Figures 6 and 7, where we present the M_{dyn} - P and M_* - P relations for 41 spiral galaxies respectively. We found M_{dyn} and M_* correlate well with P (we find a correlation coefficient of 0.74, and 0.77 with a significance of 99.99%, and 98.4% respectively).

This is a moderate correlation. The fitting results of M_{bul}– P correlations are presented in Table 3.

Recent studies have begun to discover the importance of the SMBHs in the evolution, or co-evolution, of their host galaxies (e.g., Magorrian et al. 1998, Gebhardt et al. 2000, Marconi and Hunt 2003, Springel et al. 2005, Hopkins et al. 2007, Rosario et al. 2010, Treuthardt et al. 2012).

Also, a recently discovered important relation between the spiral arm pitch angle of a galaxy and the SMBH mass, the M–P relation was presented by Seigar et al. (2008), whereas Feoli and Mancini (2009) found the relation between $M_{bul}\sigma^2$ and SMBH mass.

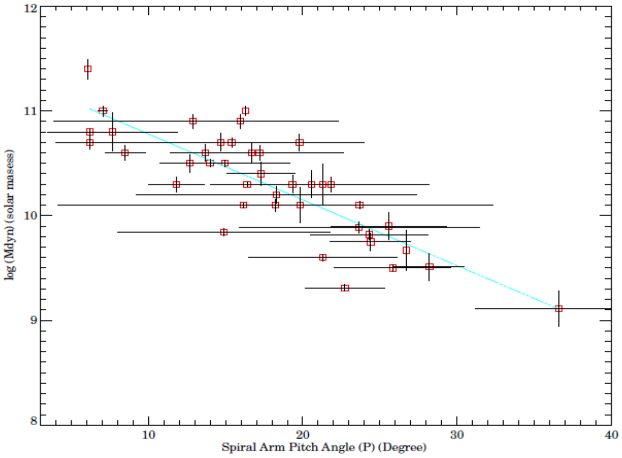

Figure 6. The bulge dynamical masses as a function the spiral arm pitch angle. The solid line is the fit to all spiral galaxies

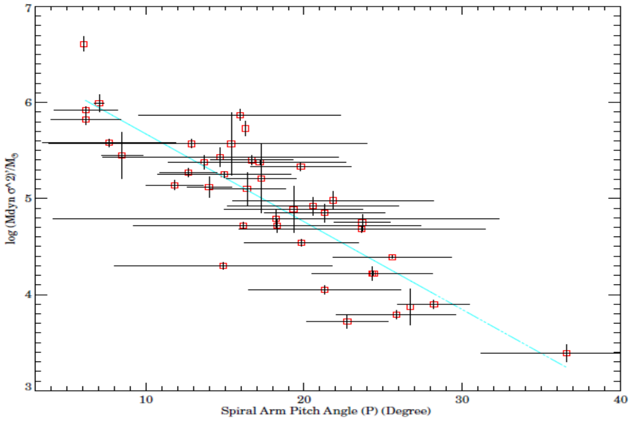

Figure 7. The bulge stellar masses as a function the spiral arm pitch angle. The solid line is the fit to all spiral galaxies.

In Figures 8 and 9 we show the bulge (dynamical and stellar) kinetic energy of random motions as a function of the spiral arm pitch angle for 41 spiral galaxies. $M_{dyn}\sigma^2$ and $M_*\sigma^2$ correlate with P (we find a correlation coefficient of 0.74, and 0.79 with a significance of 99.9%, and 99.7% respectively). It is evident that there is a moderate correlation relating $M_{bul}\sigma^2$ with P. The fitting results of M_{BH}-$M_{bul}\sigma^2$ correlations are presented in Table 3. In Table 4, we compare the fits of our relationship with the previous studies.

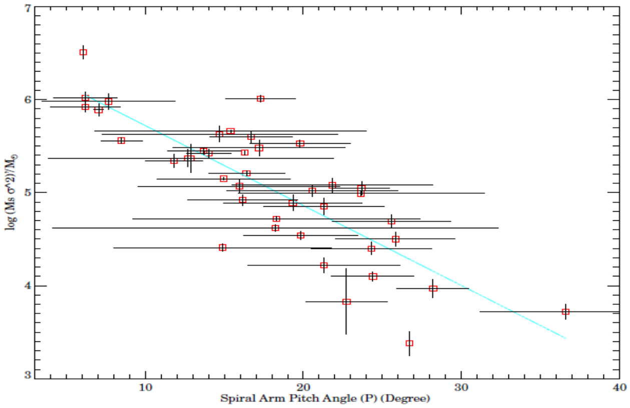

Figure 8. The kinetic energy of random motions for bulge dynamical mass as a function the spiral arm pitch angle. The solid line is the fit to all spiral galaxies

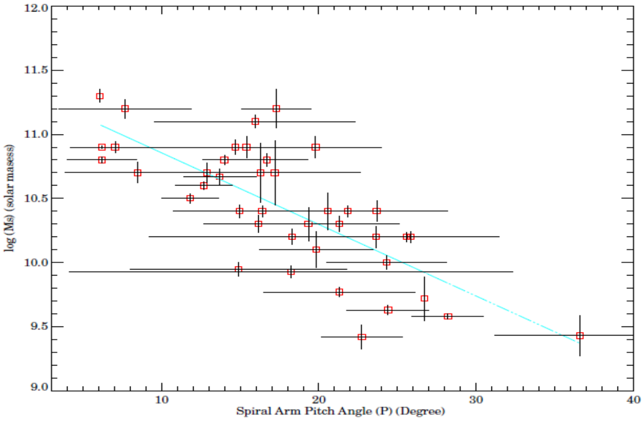

Figure 9. The kinetic energy of random motions for bulge dynamical mass as a function the spiral arm pitch angle. The solid line is the fit to all spiral galaxies.

Conclusion

In this study, we presented the bulge dynamical and stellar masses in 35 spiral galaxies, estimated by applying the isothermal model and the calibration by Oh et al. (2008) respectively. Furthermore, we found the kinetic energy of random motions of the corresponding host galaxies using $M_{dyn}\sigma^2$ and $M_{s*}\sigma^2$.

We have obtained the best-fit lines of four scaling relations. Among them, we found that M_{dyn} - P, M_* - P, $M_{dyn}\sigma^2$ - P, and $M_*\sigma^2$– P have a linear correlation coefficient 8.23, 7.56, 7.78, and 7.29 respectively. In other words, both the stellar and dynamical masses of bulges correlate well with spiral arm pitch angle. Furthermore, the kinetic energies of random motions in the bulge (whether determined from stellar or dynamical mass) correlates well with pitch angle too.

Hence, pitch angle is a good instrument to determine indirect measurements of the dynamical bulge mass, stellar bulge mass, and the kinetic energy (dynamical and stellar) of random motions in bulges.

Table 1. Estimated Galaxy Parameters.

Name (1)	Leda Type (2)	σ (km/sec) (3)	P (deg.) (4)	SMBH (M_{BH}-σ) (6)	$M_{dyn}(M_\odot)$ (7)	$M_s(M_\odot)$ (8)	$M_{dyn}\sigma^2$ (9)	$M_s\sigma^2$ (10)
Circinus	Sb	75 (1)	26.7	6.418±0.1	9.67±0.190	9.72±0.17	3.87±0.19	3.883±0.13
IC 2560	SBb	137 (1)	16.3	7.469±0.2	11±0.047	10.7±0.23	5.732±0.075	5.433±0.023
NGC 224	Sb	160±8 (2)	8.5±1.3	7.794±0.23	10.6±0.071	10.7±0.08	5.458±0.238	5.568±0.035
NGC 613	Sbc	125.3±18.9 (3)	23.68±1.77	7.309±0.2	10.1±0.035	10.4±0.08	4.755±0.083	5.055±0.071
NGC 1022	SBa	99 (4)	19.83±3.6	6.902±0.3	10.1±0.170	10.1±0.14	4.541±0.036	4.541±0.047
NGC 1068	Sb	151±7 (5)	17.3±2.2	7.639±0.05	10.4±0.11	11.2±0.15	5.217±0.36	6.017±0.035
NGC 1097	SBb	150 (6)	16.7±2.62	7.627±0.18	10.6±0.094	10.8±0.047	5.402±0.048	5.602±0.065
NGC 1300	Sbc	218±10 (7)	12.7±1.8	7.568±0.17	10.5±0.085	10.6±0.031	5.272±0.047	5.372±0.094
NGC 1350	Sab	120.91±2.08 (8)*	20.57±5.38	7.251±0.04	10.3±0.13	10.4±0.142	4.924±0.094	5.024±0.058
NGC 1353	Sb	83 (9)	36.6±5.4	6.594±0.13	9.11±0.73	9.43±0.057	3.394±0.085	3.728±0.083
NGC 1357	Sab	121±14 (10)	16.16±3.48	7.252±0.03	10.1±0.023	10.3±0.067	4.726±0.032	4.925±0.059
NGC 1365	Sb	151±20 (11)	15.4±2.4	7.639±0.07	10.3±0.025	10.4±0.045	5.105±0.17	5.217±0.027
NGC 1398	SBab	216±20 (12)	6.2±2	8.264±0.08	10.8±0.023	10.9±0.013	5.928±0.037	6.028±0.058
NGC 1433	SBab	84±9 (13)	25.82±3.79	6.615±0.05	9.5±0.034	10.2±0.043	3.798±0.046	4.508±0.07
NGC 1566	SABb	100±10 (14)	21.31±4.78	6.919±0.07	9.6±0.032	9.77±0.037	4.056±0.048	4.221±0.083
NGC 1672	Sb	130.8±2.09 (8)*	18.2±14.07	7.388±0.14	10.1±0.057	9.93±0.046	4.793±0.094	4.623±0.036
NGC 1808	Sa	148 (9)	23.65±7.77	7.601±0.11	9.89±0.053	10.2±0.083	4.23±0.035	4.991±0.025
NGC 2442	Sbc	140.74±2.18 (8)*	14.95±4.2	7.516±0.12	10.5±0.032	10.4±0.048	5.256±0.032	5.153±0.015
NGC 3031	Sab	143±7 (7)	15.4±8.6	7.544±0.04	10.7±0.046	10.9±0.085	5.576±0.328	5.664±0.01
NGC 3227	SABa	128±13 (7)	12.9±9	7.35±0.16	10.9±0.065	10.7±0.074	5.574±0.043	5.3744±0.15
NGC 3368	SABa	122±28 (7)	14±1.4	7.267±0.06	10.5±0.037	10.8±0.034	5.122±0.11	5.422±0.047
NGC 3511	SABc	93.56±2.04 (8)*	28.21±2.27	6.803±0.07	9.51±0.13	9.58±0.019	3.902±0.042	3.972±0.096
NGC 3521	SABb	130.5±7.1 (15)	21.86±6.34	7.384±0.05	10.3±0.071	10.4±0.045	4.981±0.094	5.081±0.073
NGC 3673	Sb	117.45±2.07 (8)*	19.34±4.38	7.2±0.011	10.3±0.083	10.3±0.13	4.899±0.240	4.899±0.084
NGC 3783	SBab	95±10 (16)	22.73±2.58	6.83±0.021	9.31±0.032	9.42±0.094	3.725±0.075	3.835±0.35
NGC 3887	Sbc	102.01±2.05 (8)*	24.4±2.6	6.954±0.04	9.75±0.084	9.63±0.038	4.227±0.023	4.107±0.051
NGC 4030	Sbc	122.43±2.1 (8)*	19.8±3.2	7.544±0.06	10.7±0.082	10.9±0.084	5.335±0.046	5.535±0.037
NGC 4151	SABa	156±8 (7)	11.8±1.8	7.696±0.07	10.3±0.071	10.5±0.036	5.146±0.048	5.346±0.072
NGC 4258	SABb	146±15 (7)	7.7±4.2	7.58±0.012	10.8±0.18	11.2±0.074	5.588±0.041	5.988±0.084

Table 1. Estimated Galaxy Parameters. *continued*

NGC 4462	SBab	146±8 (17)	17.2±5.42	7.579±0.02	10.6±0.074	10.7±0.25	5.388±0.026	5.485±0.081
NGC 4594	Sa	240±12 (7)	6.1	8.448±0.01	11.4±0.092	11.3±0,049	6.6104±0.07	6.5104±0.07
NGC 4699	SABb	215±10 (18)	6.2±2.2(1)	8.256±0.05	10.7±0.067	10.8±0.024	5.824±0.053	5.924±0.053
NGC 5054	Sbc	104.48±2.05 (8)*	25.57±3.73	6.996±0.06	9.9±0.13	10.2±0.036	4.398±0.012	4.698±0.071
NGC 5055	Sbc	101±5 (15)	14.9±6.9	6.937±0.08	9.84±0.037	9.95±0.054	4.308±0.036	4.418±0.043
NGC 6300	SBb	94±5 (3)	24.3±3.8	6.811±0.05	9.82±0.046	10±0.053	4.226±0.073	4.406±0.068
NGC 6744	SABb	112±25 (19)	21.28±3.8	7.117±0.07	10.3±0.19	10.3±0.059	4.858±0.093	4.858±0.091
NGC 6902	SBab	145.86±2.1 (8)*	13.71±2.3	7.578±0.04	10.6±0.084	10.67±0.05	5.387±0.073	5.457±0.035
NGC 7213	Sa	185±20 (17)	7.05±0.28	7.993±0.03	11±0.048	10.9±0.046	5.994±0.087	5.894±0.064
NGC 7531	SABb	108.7±5.6 (9)	18.31±9.09	7.065±0.09	10.2±0.083	10.2±0.059	4.722±0.072	4.752±0.021
NGC 7582	SBab	137±20 (7)	14.7±7.44	7.469±0.09	10.7±0.086	10.9±0.057	5.433±0.097	5.613±0.082
NGC 7727	SABa	181±10 (20)	15.94±6.39	7.955±0.07	10.9±0.064	11.1±0.049	5.875±0.058	6.075±0.079

Columns: **(1)** galaxy name. **(2)** Hubble type taken from the Hyper-Leda catalogue. **(3)** Velocity dispersion in km/s, Velocity dispersion references: (1) Hu 2009 (2) Lucey et al. 1997 (3) Beifior et al. 2009 (4) Garcia-Burillo et al. 2003 (5) Gültekin et al. 2009 (6) Davies 2009 (7) Sani 2011 (8) Ferrarese 2002 (9) Douglas 1995 (10) Lauer 2007 (11) Oliva 1995 (12) Whitmore 1985 (13) Buta 2011 (14) Nelson 1995 (15) Ho et al. 2009 (16) Greene et al. 2006 (17) Idiart et al. 1996 (18) Bower et al. 1993 (19) Benttoni et al. 1997 (20) Lake 1986. **(5)** Spiral arm pitch angle (P). Most of (P) taken from Berrier et al. (2013), and Davis et al. (2012). The spiral arm pitch angle given for M31, MW, and NGC 4945 are taken from Braun (1991), and Levine et al. (2006) respectively. **(6)** $\log(M_{BH}/M_{\odot})$ calculated by using M_{BH}-σ relation. (**7**) dynamical bulge mass. **(8)** Stellar bulge mass. **(9)** The kinetic energy for dynamical bulge mass ($M_{dyn}\sigma^2$). **(10)** the kinetic energy for stellar bulge mass ($M_{dyn}\sigma^2$).

Table 2. Regression results for log *M*•= *b*+ *m*log*x* with the sample consisting of 41 spiral galaxies

Relation	b	m	r
M_{BH} - M_d	-0.46 ± 0.04	0.76 ±0.06	0.84, 100%
M_{BH} – M_s	-0.57 ± 0.07	0.76 ±0.09	0.81, 100%
M_{BH} - P	8.37 ± 0.65	-0.05 ± 0.004	-0.82, 99.25%
M_{BH} – $M_d\ \sigma^2$	4.41 ± 0.03	0.59 ± 0.05	0.87, 100%
M_{BH} – $M_s\sigma^2$	4.38 ± 0.04	0.58± 0.03	0.85, 100%
M_d - P	11.4 ± 0.15	-0.06 ± 0.005	-0.82, 99.24%
M_s - P	11.41 ± 0.32	-0.05 ± 0.002	0.75, 98.95%
$M_d\ \sigma^2$- P	6.59 ± 0.43	-0.09 ± 0.005	-0.77, 99.06
$M_s\ \sigma^2$-P	6.58 ± 0.049	-0.08 ± 0.007	0.72, 98.79%

Table 3. Scaling relation for $\log M_\bullet = b + m\log x$ with the sample of 41 spiral galaxies

Relation	
M_{BH} - M_d	$\log_{10} M_{BH} = (-0.46\pm0.04) + (0.76 \pm 0.06) \log_{10} (M_{dyn})$
M_{BH} – M_s	$\log_{10} M_{BH} = (-0.57\pm0.07) + (0.76\pm0.09) \log_{10} (M_s)$
M_{BH} - P	$\log_{10} M_{BH} = (8.37\pm0.65) - (0.05 \pm 0.004)$ P
M_{BH} – $M_d\ \sigma^2$	$\log_{10} M_{BH} = (4.41\pm0.03) + (0.59 \pm0.05) \log_{10} (M_{dyn}\sigma^2)$
M_{BH} – $M_s\ \sigma^2$	$\log_{10} M_{BH} = (4.38\pm0.04) + (0.58\pm0.03) \log_{10} (M_s\ \sigma^2)$
M_d - P	$\log_{10} M_d = (11.4\pm0.15) - (0.06\pm0.005)$ P
M_s - P	$\log_{10} M_s = (11.41\pm0.32) - (0.05\pm0.002)$ P
$M_d\ \sigma^2$- P	$\log_{10} M_{dyn}\sigma^2 = (6.58\pm0.43) - (0.09\pm0.005)$ P
$M_s\ \sigma^2$-P	$\log_{10} M_s\sigma^2 = (16.13\pm0.43) - (0.08\pm0.007)$ P

Table 4. Comparisons with previous studies

Relation	a	b	r	References
M_{BH} - M_d	-1.64 ± 2.55 -9.01 ± 1.96 -1.05 ±2.00	0.87 ±0.25 1.58 ± 0.10 0.81 ± 0.2	0.68	Benedetto et al. 2013
M_{BH} - P	8.21 ± 0.16 8.44 ± 0.10	-0.062 ± 0.009 -0.076 ± 0.005	-0.81, 99.7% -0.91, 99.99%	Berrier et al. 2013 Seigar et al. 2008
M_{BH} – $M_d\ \sigma^2$	4.55 ± 0.8 2.36 ± 0.62 4.88 ± 0.56	0.75 ± 0.22 1.37 ± 0.17 0.66 ± 0.16	0.68	Benedetto et al. 2013

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