THE GALACTIC SPIN OF AGN GALAXIES

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ABSTRACT

Using an extensive sample of galaxies selected from the Sloan Digital Sky Survey Data Release 5, we compare the angular momentum distribution of active galactic nuclei (AGNs) with non-AGN hosting late-type galaxies. To this end we characterize galactic spin through the dimensionless angular momentum parameter $\lambda$, which we estimate through simple dynamical considerations. Using a volume-limited sample, we find a considerable difference when comparing the empirical distributions of $\lambda$ for AGNs and non-AGN galaxies, the AGNs showing typically low $\lambda$ values and associated dispersions, while non-AGNs present higher $\lambda$ values and a broader distribution. A more striking difference is found when looking at $\lambda$ distributions in thin $M_*$ cuts; while the spin of non-AGN galaxies presents an anticorrelation with $M_*$, with bright (massive) galaxies having low spins, AGN host galaxies present uniform values of $\lambda$ at all magnitudes, a behavior probably imposed by the fact that most late-type AGN galaxies present a narrow range in color, with a typical constant $\lambda$ value. We also find that the fraction of AGN hosting galaxies in our sample strongly depends on galactic spin, increasing dramatically for decreasing $\lambda$. For AGN host galaxies, we compute the mass of their supermassive black holes and find that this value tends to be higher for low spin galaxies, even at fixed luminosity, a result that could account, to a certain extent, for the spread on the luminosity–black-hole mass relation.

Key words: galaxies: active – galaxies: fundamental parameters – galaxies: spiral – galaxies: statistics – galaxies: structure

Online-only material: color figures

1. INTRODUCTION

Studies of central gas and stellar kinematics of nearby galaxies have revealed the presence of supermassive black holes (SMBHs) in almost all massive galaxies. According to the most accepted paradigm (Rees 1984), galactic nuclear activity is directly related with the fueling process of these SMBHs, which strongly correlates to the overall structure and evolution of the galaxies. For instance, active galactic nucleus (AGN) activity seems to be triggered only in galaxies with massive bulges and intermediate colors, as pointed out by Choi et al. (2009), henceforth CWP09. These authors show how the necessary conditions for AGN activity depend on galaxy morphology; for early-type galaxies low velocity dispersion and blue colors are preferred, and indicative of available gas supply for the central black hole, while intermediate velocity dispersion, intermediate-color, and more concentrated late-type galaxies are more likely to host AGNs, reinforcing the idea that AGN host galaxies are intermediate objects between the red sequence and the blue cloud (Kauffmann et al. 2003).

If most galaxies have SMBHs in their centers, a fundamental question is why all of them do not host AGNs when gas supply is available. This is a question with no simple answer given the complexity of the processes involved in the formation and evolution of galaxies, but important clues have been proposed to elucidate the mechanisms that trigger AGN activity (Martini 2004). Major mergers of gas-rich progenitors and galaxy interactions are two commonly invoked mechanisms that can provide gas to the center of the galaxies and fuel dormant SMBHs (Hopkins et al. 2006; Ellison et al. 2008). Tidal torques exerted by non-axisymmetric features such as large-scale and nuclear bars (Jogee 2006), recycled gas from dying stars in the inner kiloparsecs of the galaxy (Ciotti & Ostriker 2007), and enhanced viscosity of the turbulence associated with supernova explosions (Chen et al. 2009) are just some other mechanisms that can effectively trigger nuclear activity.

A common requirement for any of the mentioned mechanisms is the removal of specific angular momentum in order for the material to collapse to the center and operate as fuel. Therefore, a relation between the overall galactic $\lambda$ spin parameter and the onset of AGN activity is expected, with a higher frequency of AGNs in low spinning galaxies. Statistically, AGN hosting galaxies should form a low $\lambda$ population, in comparison to normal galaxies. Low angular momentum is expected not only in the growing phase of SMBHs, but has also been invoked to explain the formation of massive black hole seeds themselves. In this scenario (Eisenstein & Loeb 1995; Koushiappas et al. 2004), the direct collapse of low angular momentum material results in a typical inverse proportionality between the SMBH mass and the total angular momentum (Haehnelt et al. 1998; Colgate et al. 2003).

In this work, we study the spin distribution of AGN host galaxies in contrast with non-AGNs, parameterizing the angular momentum through the dimensionless spin parameter

$$\lambda = \frac{L}{GM^2}. \quad (1)$$

where $E$, $M$, and $L$ are the total energy, mass, and angular momentum of the configuration, respectively (Peebles 1969). Our aim is to determine empirically if the AGN population effectively presents a low spin distribution when compared with non-AGNs and corroborate the results arising from theoretical studies concerning the relation between $\lambda$ and the SMBH mass.
To this end, we use a sample of galaxies selected from the Sloan Digital Sky Survey (SDSS) and apply a simple model to obtain an empirical estimation of $\lambda$. The large volume-limited sample allows a thorough coverage of parameter space, which permits an empirical determination of the leading galactic physical parameters driving the AGN phenomena and the observed scalings with SMBH mass. The physical model is presented in Section 2, and the sample selection criteria in Section 3. In Section 4, we present our general results and the final conclusions are summarized in Section 5.

2. ESTIMATION OF THE SPIN FROM OBSERVABLE PARAMETERS

In Hernandez & Cervantes-Sodi (2006), we derived a simple estimate of $\lambda$ for disk galaxies in terms of observational parameters and showed some clear correlations between this parameter and type defining structural parameters. Here we briefly recall the main ingredients of the simple model. The model considers only two components, a disk for the baryonic component with an exponential surface mass density $\Sigma(r)$,

$$\Sigma(r) = \Sigma_0 e^{-r/R_d},$$

(2)

where $r$ is a radial coordinate, and $\Sigma_0$ and $R_d$ are two constants which are allowed to vary from galaxy to galaxy, and a dark matter halo having a singular isothermal density profile $\rho(r)$, responsible for establishing a rigorously flat rotation curve $V_d$ throughout the entire galaxy:

$$\rho(r) = \frac{1}{4\pi G} \left( \frac{V_d}{r} \right)^2.$$  

(3)

In this model we are further assuming that (1) the specific angular momentum of the disk and halo are equal (e.g., Mo et al. 1998; Zavala et al. 2008); (2) the total energy is dominated by that of the halo which is a virialized gravitational structure; and (3) the disk mass is a constant fraction of the halo mass, $F = M_d/M_H$. These assumptions allow us to express $\lambda$ as

$$\lambda = \frac{2^{1/2}V_d^2R_d}{GM_H}.$$  

(4)

Finally, we introduce a baryonic Tully–Fisher (TF) relation:

$$M_d = A_FV_d^{5.5}$$

(e.g., Gurovich et al. 2004). Taking the Milky Way as a representative example, we evaluate $F$ and $A_F$ to obtain

$$\lambda = 21.8 \frac{R_d/kpc}{(V_d/km \, s^{-1})^{3/2}}.$$  

(5)

We proved the accuracy in our estimation of $\lambda$ in Cervantes-Sodi et al. (2008), comparing the estimation using Equation (5) to values arising from numerical simulations of six distinct groups, where the actual value of $\lambda$ is known, as it is one of the parameters of the simulated galaxies, and where this can also be estimated through Equation (5), as baryonic disk scale lengths and disk rotation velocities are part of the output. The result was a one-to-one correlation, with very small dispersion and no bias, leading to typical errors <30%, which we include throughout. The use of this estimate for large SDSS samples led us in Hernandez et al. (2007) and Cervantes-Sodi et al. (2008) to a first empirical derivation of the distribution of $\lambda$ parameters in the local universe and a measure of the scalings of this parameter with local environment and halo mass. These results were latter confirmed by Berta et al. (2008) using an estimate of $\lambda$ through Equation (5), also used by Gogarten et al. (2010) as an unbiased first-order $\lambda$ measurement.

3. THE SDSS SAMPLE

The sample of galaxies used in this work is an enhanced version of the study by CWP09. The galaxies come from the large-scale structure sample, DR4plus, using the New York University Value-Added Galaxy Catalogue (VAGC; Blanton et al. 2005), which is a galaxy subset of the SDSS Data Release 5 (Adelman-McCarthy et al. 2006), and the Korea Institute for Advanced Study-VAGC (Choi et al. 2010). A detailed description of the sample can be found in Choi et al. (2007) and CWP09. The rest-frame absolute magnitudes of individual galaxies were computed in the $r$ band, using Galaxy reddening correction (Schlegel et al. 1998) and $K$-corrections as described by Blanton et al. (2003), with a mean evolution correction given by Tegmark et al. (2004). We define a volume-limited sample with a lower magnitude cutoff $M_r = -19.0$, with redshifts $0.020 < z < 0.086$, and a total number of 87,590 galaxies. Disk scale lengths are estimated from one-component light fits, which implicitly account for the presence of low angular momentum material in bulges.

In order to compare the spin of AGN and non-AGN galaxies, we use only Type II AGNs to avoid complications due to the presence of a bright nucleus. The AGN galaxies were segregated from star-forming galaxies using the flux ratio BPT diagram of Balmer and ionization lines (Baldwin et al. 1981). The AGNs were selected among galaxies fulfilling the definition by Kewley et al. (2006):

$$0.61/\log([\mathrm{N}\,\mathrm{II}]/H\alpha) - 0.47 + 1.19 < \log([\mathrm{O}\,\mathrm{III}]/H\beta),$$

$$0.72/\log([\mathrm{S}\,\mathrm{II}]/H\alpha) - 0.32 + 1.30 < \log([\mathrm{O}\,\mathrm{III}]/H\beta),$$

$$0.73/\log([\mathrm{O}\,\mathrm{I}]/H\alpha) + 0.59 + 1.33 < \log([\mathrm{O}\,\mathrm{III}]/H\beta),$$

while star-forming galaxies were selected using the selection criteria by Kauffmann et al. (2003):

$$0.61/\log([\mathrm{N}\,\mathrm{II}]/H\alpha) - 0.05 + 1.30 < \log([\mathrm{O}\,\mathrm{III}]/H\beta),$$

$$0.72/\log([\mathrm{S}\,\mathrm{II}]/H\alpha) - 0.32 + 1.30 < \log([\mathrm{O}\,\mathrm{III}]/H\beta),$$

$$0.73/\log([\mathrm{O}\,\mathrm{I}]/H\alpha) + 0.59 + 1.33 < \log([\mathrm{O}\,\mathrm{III}]/H\beta),$$

requiring a signal-to-noise ratio $\geq$6. The galaxies residing in the area between the previous demarcation lines (solid and dotted lines, respectively, in Figure 1) are identified as composite objects, which contain AGNs as well as extended H\textsc{ii} regions.
Our non-AGN sample consists of those galaxies excluding AGNs and composite galaxies, without signal-to-noise cut.

To estimate the black hole mass \( M_{\text{BH}} \), we use the \( M_{\text{BH}} \)-stellar velocity dispersion relation by Tremaine et al. (2002):

\[
\log(M_{\text{BH}}/M_\odot) = 8.13 + 4.02 \times \log(\sigma/200 \text{ km s}^{-1}),
\]

where a simple aperture correction to the stellar velocity dispersion was applied. Since velocity dispersion measurements lower than the instrumental resolution are not robust, we will focus on AGNs with \( M_{\text{BH}} > 10^6 M_\odot \).

In order to discriminate between elliptical and disk galaxies, we used the prescription of Park & Choi (2005) in which early (ellipticals and lenticulars) and late (spirals) types are segregated in a \( u-r \) color versus \( g-i \) color gradient space and in the concentration index space. They extensively tested the selection criteria through a direct comparison of visually assigned types for a large sample of several thousand galaxies. The specific selection criteria can be found in Park & Choi (2005). For more details the reader is referred to CPW09.

4. RESULTS

Our Equation (5) requires the rotational velocity to calculate \( \lambda \), which is inferred from the absolute magnitude in the \( r \)-band and using a TF relation (Pizagno et al. 2007). To avoid the problem of internal absorption in edge-on galaxies (Cho & Park 2009), and consequently underestimating rotational velocities, we limit the sample to spiral galaxies having seeing-corrected isophotal axis ratios \( b/a > 0.6 \).

Once the galaxies in our sample are segregated into early- and late-type galaxies, and into different activity classes such as normal, composite, and AGN hosting galaxies, we computed \( \lambda \) using Equation (5) for all the late-type galaxies and obtained the spin distribution for the three different subclasses: 41,662 normal, 2273 composite, and 1026 AGNs. Figure 2(a) shows the distribution of \( \lambda \) values for normal, composite, and AGN late-type host galaxies. We can see a clear difference between the normal and the AGN population, the former showing typically higher spin values with a large dispersion compared with the latter, which is a more coherent population of low spin galaxies. The distribution of galaxies classified as composite follows almost exactly the same distribution as AGN galaxies, probably due to the low number of misclassified star-forming galaxies. Given that these galaxies are actually a mixed group of AGN and non-AGN galaxies we will not consider them for the rest of the analysis, and we will focus only in the difference between AGNs and normal galaxies.

Theoretical (Shaw et al. 2006), as well as empirical (Hernandez et al. 2007), distributions of \( \lambda \) are commonly
described by a log-normal function; in our case, the values describing the non-AGN and AGN distributions are, respectively, \( \lambda_0 = 0.059 \pm 0.006, \sigma_1 = 0.400 \pm 0.005 \) and \( \lambda_0 = 0.042 \pm 0.004, \sigma_1 = 0.350 \pm 0.003 \), showing a clear difference between the two populations.

We use the two sample Kolmogorov–Smirnov test to compare the distributions of normal and AGN host galaxies to determine whether they are drawn from the same parent distribution. The result of the test yields a negligible probability of \( P \sim \times 10^{-180} \) that the two samples are drawn from the same parent distribution.

If we look at the \( \lambda \) distribution of normal galaxies, splitting the sample according to the absolute magnitude (Figure 2(b)), we clearly see that the distributions get tighter and present lower mean \( \lambda \) values for brighter galaxies; this is the same behavior we reported in Cervantes-Sodi et al. (2008), where we found that massive galaxies tend to have low spin dark matter halos and show low dispersion, while low mass galaxies have higher \( \lambda \) values and high dispersions around the median value, a result later confirmed by Berta et al. (2008). A striking difference appears for the case of AGN host galaxies (Figure 2(c)), which show low mean \( \lambda \) values and tight distributions for all \( M_r \). This result indicates that only low spinning galaxies, at all mass ranges, are suitable AGN hosts in the local universe.

Previous work has already pointed out that the recurrence of AGN activity is a function of internal properties such as absolute magnitude, color, and velocity dispersion. Kauffmann et al. (2003) state that massive galaxies with old stellar populations frequently host AGNs and CWP09 found that the fraction of AGN increases with galaxy luminosity, and particularly for late-type galaxies, this fraction increases for intermediate color systems, with \( u - r = 2.5 \sim 2.4 \) and intermediate velocity dispersion (\( \sim 130 \) km s\(^{-1}\)). In this context, most of our AGN hosting galaxies are restricted to having intermediate colors, a restriction that also constrains the value of \( \lambda \) given that color anticorrelates with \( \lambda \) (Hernandez & Cervantes-Sodi 2006). To make a fair comparison between AGN and non-AGN galaxies, we constructed a control sample by selecting non-AGN galaxies that match one to one the morphology, absolute magnitude, color, and concentration index of each galaxy in the AGN sample, guaranteeing that the distributions of these parameters are the same for both populations. Figure 2(d) shows how the typical \( \lambda \) value of AGN hosting galaxies tends to be lower than the one presented by the control sample at all \( M_r \) values. The uncertainties (throughout this paper) represent 1\( \sigma \) confidence intervals determined by the bootstrap resampling method.

A natural question arising from our previous results is whether or not the AGN fraction depends on galactic spin. Previous studies have shown the dependence of the AGN fraction on the brightness of the parent galaxies (Mercurio et al. 2010, CWP09), or their associated stellar or total mass (Pasquali et al. 2009). Figure 3(a) shows the fraction of AGN+composite (\( f_{AGN+Composite} \)) galaxies as a function of absolute magnitude in different \( \lambda \) cuts, where a moderate increase of \( f_{AGN+Composite} \) is present for increasing brightness, while a large difference in this fraction is evident for the distinct \( \lambda \) cuts. Figure 3(b) gives a complementary study for \( f_{AGN+Composite} \) as a function of galactic spin for thin \( M_r \) slices, where the dependence on \( \lambda \) appears stronger than the case of \( M_r \), with all curves consistent with a single underlying dependence to within errors, for all magnitude bins. This shows that the driving physical ingredient is the value of \( \lambda \) rather than magnitude.

CPW09 have already shown that late-type galaxies present weak dependence of \( f_{AGN+Composite} \) on magnitude or mass (accounted for through velocity dispersion) in addition to \( u - r \) color, and in the preceding section we found that the value of \( \lambda \) is intimately linked to the color of the galaxy in question. The \( f_{AGN+Composite} \) dependency on \( \lambda \) for narrow \( u - r \) bins is presented in Figure 3(c), where even at fixed color, a substantial decrease of the AGN fraction results as \( \lambda \) increases, at least in the range of colors where the highest occurrence of
AGNs is found. We see that regardless of mass or color, high \( \lambda \) systems will only very rarely present an AGN.

The tight correlations of \( M_{\text{BH}} \) with host galaxy properties, such as the well-known one with the bulge luminosity (Kormendy & Richstone 1995) or the tighter \( M_{\text{BH}} \) versus bulge velocity dispersion relation (Graham et al. 2011), have now been extended to more global properties, not related to the bulge component alone. Correlations with the spiral arm pitch angle of disk galaxies (Seigar et al. 2008), the mass of the dark matter halo (Ferreras 2002; Booth & Schaye 2010), and the total gravitational mass of the host galaxies (Bandara et al. 2009) show how the correlations are not restricted only to the bulge component and point to an SMBH–bulge–total-mass interrelation (Volonteri et al. 2011). Given the important role the spin plays in establishing the morphology and present-day structure of disk galaxies, and our previous result that shows the direct influence of \( \lambda \) on determining nuclear activity, it is logical to expect a correlation between \( \lambda \) and \( M_{\text{BH}} \) for the active galaxies in our sample, more specifically, an anticorrelation.

Let us consider the simple criterion by Larson (2010) for the formation of black holes, where gas in a forming galaxy with a column density above a critical value \( \Sigma_{\text{crit}} \) goes into forming a central black hole. If the gas in the forming galaxy is distributed radially like the total mass with an isothermal density profile given by Equation (3), with a gas to total mass ratio \( f_g \), the surface density of gas at any radius \( r \) in the disk will be \( \Sigma_g(r) = f_g V_g^2 / 2 \pi G M \). For a rotationally supported disk, the scale radius is given by \( R_d \approx \lambda r_{\text{vir}} \), where \( r_{\text{vir}} \) is the virial radius of the system. This allow us to express the mass of gas within the critical column density criterion as

\[
M_g(\Sigma < \Sigma_{\text{crit}}) = \frac{f_g M^2}{\pi \Sigma_{\text{crit}}^2 (\lambda r_{\text{vir}})^2}. \tag{7}
\]

This expression, that does not attempt to be more than a dimensional analysis estimate, implies that at fixed total mass the mass of gas that could end up forming a black hole is \( M_{\text{BH}} \propto \lambda^{-n} \), with \( n = 2 \). Theoretical studies report different values for \( n \) that fall in the range 1–4 (Colgate et al. 2003; Koushiappas et al. 2004), all of them establishing an anticorrelation between the mass of the black hole and halo spin. Figure 4 (top panel) shows the empirical dependence of the inferred \( M_{\text{BH}} \) with the spin parameter for our sample of AGN host galaxies, showing the expected anticorrelation with \( \lambda \), in this case with a best fit described by \( \log(M_{\text{BH}}) = (-0.716 \pm 0.114) \log(\lambda) + (6.455 \pm 0.155) \). In Figure 4 (bottom panel) we present the result of splitting the sample according to the absolute magnitude of the galaxies, where we can appreciate how at fixed \( \lambda \) brighter (more massive) galaxies host more massive black holes, with the anticorrelation with \( \lambda \) present at all fixed \( M \) cuts. In this case, the leading effect is the total mass, with \( \lambda \) introducing only a small but well-defined trend in the expected sense.

5. CONCLUSIONS

Using an extensive sample of galaxies extracted from the SDSS DR5, we show that the empirical distributions of the \( \lambda \) spin parameter of AGNs and non-AGN host galaxies are qualitatively and quantitatively different, the first distribution having lower \( \lambda \) values and smaller dispersion around the median when compared with the latter. Another striking difference between the two populations is that while the spin of normal galaxies presents a dependence on absolute magnitude, with a systematic decrease of \( \lambda \) with increasing luminosity, AGN host galaxies present at all \( M \) low \( \lambda \) values. This result, in addition to the increase of the AGN fraction for decreasing \( \lambda \), highlights the requirement for galaxies to have low spin in order to host AGNs and should be taken into account in semianalytic models that exclusively use the halo or stellar mass to reproduce the fraction of galaxies belonging to different activity classes (e.g., Wang & Kauffmann 2008; Fontanot et al. 2011). Seeding AGNs
into modeled dark matter halos should primarily consider $\lambda$, in order to better model the observed universe.

For the AGN sample we found that the inferred mass of the SMBHs shows a weak dependence on the spin of the hosting galaxies, with increasing mass for decreasing spin, a logical result if we need the gas to be accreted onto the central massive object, a process that can be more effectively accomplished if the raw material originally has low angular momentum. We recovered the leading $M_{\text{BH}}-\lambda$ relation at fixed absolute magnitude, with typically higher SMBH mass for brighter galaxies at fixed $\lambda$, showing a double dependence of $M_{\text{BH}}$ on $M_r$ and $\lambda$. Given that the trend with the spin is present at all $M_r$ bins, this could account, to a certain degree, for the dispersion in the well-established $M_{\text{BH}}$–luminosity relation.

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