THE ORIENTATION OF THE NUCLEAR OBSCURER OF THE ACTIVE GALACTIC NUCLEI

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ABSTRACT

We examine the distribution of axis ratios of a large sample of disk galaxies hosting type 2 active galactic nuclei (AGNs) selected from the Sloan Digital Sky Survey and compare it with a well-defined control sample of non-active galaxies. We find them significantly different, where the type 2 AGNs show both an excess of edge-on objects and deficit of round objects. This systematical bias cannot be explained by a nuclear obscurer oriented randomly with respect to the stellar disk. However, a nuclear obscurer coplanar with the stellar disk also does not fit the data very well. By assuming that the nuclear obscurer having an opening angle of \( \sim 60^\circ \), we find that the observed axis ratio distribution can be nicely reproduced by a mean tilt angle of \( \sim 30^\circ \) between the nuclear obscurer and the stellar disk.

Key words: galaxies: nuclei – galaxies: Seyfert – galaxies: spiral – galaxies: statistics

Online-only material: color figures

1. INTRODUCTION

In the unified active galactic nucleus (AGN) model, a type 2 AGN is seen from an angle close to the plane of the central accretion disk. On this plane, the accretion disk and the broad-line regions are obscured by an outer molecular torus, while a bi-polar jet emanating from the nucleus is perpendicular to the plane (Antonucci 1993). The type 1 AGNs are then these objects that we are able to see directly into the central regions.

Several studies have revealed that the angle between the orientation of the kiloparsec-scale jet and the normal to the host galaxy plane has a wide/orientation of the kiloparsec-scale jet and the normal to the plane (Antonucci 1993). The type 1 AGNs are then these objects that we are able to see directly into the central regions.

On the other hand, that AGNs are a biased sample of inclinations of stellar disks has been known for a long time. Both the optically selected (mostly type 1) and the soft X-ray-selected Seyfert galaxies show a bias against the edge-on galaxies, while the hard X-ray-selected sample do not show such a bias (Keel 1980; Lawrence & Elvis 1982; Simcoe et al. 1997; Zhang et al. 2009). McLeod & Rieke (1995) found an excess of face-on galaxies hosting both type 1 and type 2 AGNs and explained it with a substantial amount of obscuring material coplanar with the stellar disk (see also de Zotti & Gaskell 1985). Maiolino & Rieke (1995) showed that the intermediate type AGNs (1.8,1.9) are mostly found in edge-on galaxies and concluded a 100 pc scale torus coplanar with the stellar disk.

In this study, we use a large type 2 AGN sample selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000) to check whether the stellar disks of their hosts are biased to edge-on views. We then further check whether this bias is better explained by a dust layer coplanar with the galaxy plane or by an intrinsic alignment between the nuclear obscurer and stellar disk. This Letter is organized as follows. In Section 2, we study the axis ratio distribution of the AGNs and make comparisons to that of a well-defined sample of non-active disk galaxies. With the distributions of the shape parameters of the spiral disks concluded in Section 3, we then build toy models to quantify the biased axis ratios of the AGN hosts in Section 4. Finally, we make brief conclusions and discussions in Section 5.

2. THE INCLINATIONS OF THE STELLAR DISKS OF THE TYPE 2 AGN HOSTS

Our type 2 AGNs are selected from the complete spectroscopic main galaxy sample of the data release 7 (DR7; Abazajian et al. 2009) of SDSS using the empirical relation between the emission line ratios proposed by Kauffmann et al. (2003, see their Equation (1)). The emission line data are taken from the MPA-JHU DR7 release of spectrum measurements. We use the SDSS parameter \( \text{fracDeV} \) and criteria \( \text{fracDeV} < 0.5 \), which ensures that the galaxy flux is dominated by an exponential(disk) component, to select the AGNs hosted by disk galaxies. The number of the type 2 AGNs hosted by disk galaxies is then 32,618.

The inclination of a stellar disk is informed by its apparent axis ratio \( b/a \). If a disk is circular and thin, then \( b/a = \cos i \), where \( i \) is the inclination of the disk (the angle between the line of sight and the normal of the disk). If this disk is viewed from arbitrary directions, the resulted \( b/a \) follows a uniform distribution between 0 and 1.

For a more realistic triaxial ellipsoid model, the observed \( b/a \) is further dependent on two shape parameters, the disk height \( y \equiv C/A \) and the disk ellipticity \( \epsilon \equiv (1 - B/A) \), where \( A, B, C \) are the major, middle, and minor axis of the ellipsoid, respectively (Binney 1985). The \( b/a \) distribution is then dependent on both of the shape parameter \( (y, \epsilon) \) and viewing angle distributions. The galaxies with different physical properties (e.g., mass and size) are shown to have different intrinsic shape parameters (Padilla & Strauss 2008). In addition, the sample selection effects could also introduce biases into the measured \( b/a \) distribution of a galaxy sample. For example, the seeing would make the galaxies with small

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4 http://www.mpa-garching.mpg.de/SDSS/DR7/
5 \( \text{fracDeV} \) is defined in Abazajian et al. (2004) through \( \text{Fcomposite} = \text{fracDeV} \text{FdeV} + (1 - \text{fracDeV}) \text{Fexp} \), where \( \text{Fcomposite} \), \( \text{FdeV} \), and \( \text{Fexp} \) are the composite, de Vaucouleurs, and exponential fluxes of the object, respectively.
apparent sizes look rounder (Shao et al. 2007). Therefore, to quantify the inclinations of the disks of the AGN hosts, their shape parameters must be well-defined or controlled.

The AGN host galaxies are known to have distinctive physical properties. For example, the AGNs reside mostly in massive galaxies (Kaufrmann et al. 2003), and the strength of the nucleus activity is also correlated with its host property (Kaufrmann & Heckman 2009). For our sample of AGNs hosted by disk galaxies, we find that they are biased toward these hosts with large bulge component, high concentration, and old stellar population. To quantify the sample properties of these AGN hosts, we build a control sample of galaxies (without AGN phenomena) from the same galaxy catalog of SDSS, which are selected to have the same sample size and the same distributions of stellar mass, redshift, size, concentration, fracDev, and Dn(4000) (the 4000 Å break spectra index, a rough stellar age indicator) as the AGN hosts. We believe that this control sample of non-active galaxies shares the same stellar properties and selection effects (e.g., redshift distribution) as the AGN hosts so that they would have the same b/a distribution if their viewing angles were both random.

We compare the b/a distributions of the AGN hosts to the control non-active galaxies. The result is shown in the top panel of Figure 1. The AGN sample (solid histogram) has systematically higher numbers of galaxies in smaller b/a bins than the control galaxy sample (dotted histogram). For a better view of this over-density, we show the number ratios of the AGNs to the control galaxies (N_AGN/N_GAL) in different b/a bins in Figure 3. As one can see, the N_AGN/N_GAL decreases with the increasing of b/a systematically. The type 2 AGNs show both an excess of edge-on objects and deficit of round objects. Since the galaxy samples have already been controlled to have the same physical properties and selection effects as the AGN hosts, the systematical bias in b/a distribution of the AGN hosts could only be stemmed from their preferred (non-random) viewing angles. The bias toward the small axis ratios for the AGNs is basically consistent with the scenario that the nuclear obscurer is partly co-aligned with the stellar disk.

3. THE SHAPE OF THE AGN HOSTS

To quantify the preferred inclinations of the type 2 AGN hosts, the distributions of their shape parameters (γ,ε) need to be known in advance.

For the disk galaxies in general, it is found that their γ distribution can be approximated by a normal function whereas ε follows a normal or log-normal distribution (Lambas et al. 1992; Ryden 2004). However, for our control sample of galaxies, the sample selection criteria is not well-defined and the goodness of fit is also bad when only single Gaussian distributions are assumed for γ and ε/ln ε. As an alternative, the control galaxy sample can be viewed as a combination of sub-samples of galaxies, where both the γ and ε distributions follow Gaussian distributions for each sub-sample. The γ and ε distributions of the control galaxy sample are then the sum of the Gaussian distributions of these sub-samples.

We first assume 10 basis distributions for γ and ε each and then get 100 combinations of (γ, ε) distributions. Specifically, for ten γ distributions, the dispersions are fixed to 0.02, while the mean values are assigned from 0.1 to 0.5 with a step of 0.04. For ε, the peaks of the Gaussian distribution are fixed to 0 and the dispersions are taken values from 0.02 to 0.2 with a step of 0.02. Each of the (γ, ε) combination is then viewed as a sub-sample. Using Monte Carlo simulations of random viewing angles, we obtain the b/a distributions of each sub-sample. Finally, we use the non-negative least-squares linear regression technique to fit the observed b/a distribution of the control galaxies to get the fraction of each sub-sample. The final fitted b/a is shown as the dashed line in Figure 1. As we can see, the fitting is very well, which is consistent with the observed value inside Possion error in most of the b/a bins. The resulted (γ, ε) distributions reproduced from the non-negative linear regression, where the dotted lines show the contributions from different basis components (see Section 3).

(A color version of this figure is available in the online journal.)

Figure 1. b/a, γ, and ε distributions of the AGN hosts and control galaxy sample. Top panel: the b/a histograms of the AGN hosts (solid) and control galaxies (dotted). The dashed line shows the fitted histogram of the control galaxy sample from the non-negative least-squares regression. Bottom: the γ and ε distributions reproduced from the non-negative linear regression, where the dotted lines show the contributions from different basis components (see Section 3).

obtain the b/a distributions of each sub-sample. Finally, we use the non-negative least-squares linear regression technique to fit the observed b/a distribution of the control galaxies to get the fraction of each sub-sample. The fit is shown as the dashed line in Figure 1. As we can see, the fitting is very well, which is consistent with the observed value inside Possion error in most of the b/a bins. The resulted (γ, ε) distributions reproduced from the non-negative linear regression, where the dotted lines show the contributions from different basis components (see Section 3).

With (γ, ε) distributions known for the control galaxies, so that also for the AGN hosts, we move to model the viewing angles of AGN hosts.

4. THE ORIENTATION OF THE NUCLEAR OBSCURER

The biased axis ratio distribution (toward small values) of the AGN hosts implies that either the orientation of the molecular torus is correlated with the stellar disk or there is an extra dust layer aligned with stellar disk. We denote these two different obscuring scenarios as the “aligned torus model” and “stellar dust model,” respectively, below.

We parameterize the inclination of the dust torus as i_T, where i_T (0° ≤ i_T ≤ 90°) is the angle between the normal of the torus plane and the line of sight. Correspondingly, the inclination of the stellar disk is denoted as i_S. The tilt angle between the torus plane and stellar disk is then denoted as ΔTS.

4.1. The Obscurer: Aligned Torus Model

In the aligned torus model, we assume that the obscuring torus has an opening angle 2θ_T. Obviously, a type 2 AGN satisfies the criteria 90° − i_T < θ_T. A schematic of such a torus model
is shown in Figure 2. The ΘT and the tilt angle ΔTS are then the two free parameters in this model.

ΘT could be constrained from the type 2 AGN fraction f2 since f2 = sin(ΘT). The studies on the local Seyfert galaxies and the statistics of active galaxies in SDSS have shown that f2 is in the range of 70%–90% for the low luminosity AGNs (Ho et al. 1997; Simpson 2005), corresponding to 45° < ΘT < 65°. Thus, we take 45° and 65° as the low and up limits of ΘT. Inside this range, ΘT is set as a free parameter.

For tilt angle ΔTS, it is a reasonable assumption that the most probable orientation of the torus plane is to be the same as the stellar disk, i.e., P_{max}(iS) = P(ΔTS = 0), but with significant scatters on ΔTS. On the other hand, cos(ΔTS) would follow a uniform distribution between 0 and 1 if the orientations of the torus plane and the stellar disk were independent. Thus, we further assume that cos(ΔTS) follows a Gaussian distribution which peaks at ΔTS = 0 and has a scatter cos(ΔTS,m). Under the assumption of the Gaussian distribution, ΔTS,m could be viewed as an effective tilt angle, within which 68% of the ΔTS’s are smaller.

With ΘT and ΔTS,m assigned, we make Monte Carlo simulations to predict the number ratios $N_{AGN}/N_{GAL}$ in different $b/a$ bins. Specifically, we first generate a large Monte Carlo sample of galaxies with random viewing angles and ($γ, ϵ$) distributions as shown in Figure 1. For each galaxy with viewing angle $(iS,iT,iT,iT,iT,iT)$, we get the inclination of the torus plane $i_{T,iT,iT,iT,iT,iT}$ by assuming a random $φ_{T,iT,iT,iT,iT,iT}$, where $φ_{T,iT,iT,iT,iT,iT}$ and $φ_{S,iT,iT,iT,iT,iT}$ are the position angles of the torus plane and stellar disk, respectively. After that, we get a modeling type 2 AGN sample by applying the criteria 90° – $i_{T,iT,iT,iT,iT,iT}$ < ΘT for all Monte Carlo galaxies. The other galaxies with 90° – $i_{T,iT,iT,iT,iT,iT}$ > ΘT are classified as type 1 AGNs.

In the observed type 2 AGN sample, there are contaminations of intermediate type AGNs, which show weak broad wings on the Hα lines but are classified as “galaxies” by the SDSS spectroscopic pipeline. The fraction of these intermediate type contaminations is estimated to be about 8% from eyeball classifications (Kauffmann et al. 2003; Simpson 2005). To mimic this intermediate type AGN contaminations in our model as well, we also put some type 1 AGNs into our type 2 AGN sample randomly as contaminations, up to the maximum of 8% of the total sample.

For each Monte Carlo simulation, we randomly select 50,000 objects from the resulted library of type 2 AGNs (including type 1 contamination). For each parameter set of ΘT and ΔTS,m, we run the simulation 30 times to account for the Possion fluctuation. We normalize the $b/a$ histograms of the model galaxies to be the same as the model AGNs and calculate $N_{AGN}/N_{GAL}$ in $b/a$ bins as that done for observations. The mean values of the 30 simulations are taken as the model output for each parameter set. Finally, we use the least-squares routine to search the best model parameters of ΘT and ΔTS,m by fitting the observed $N_{AGN}/N_{GAL}$ in different $b/a$ bins. The best model fitting is shown as the dashed line in Figure 3, which has the minimum $χ^2_{min}$ ≈ 9, comparable to the number of data points (9 $b/a$ bins), indicating an excellent goodness of fit.

The best model parameters are ΘT = 58° and ΔTS,m = 37°, respectively. ΘT = 58° corresponds to a type 2 AGN fraction of f2 = 0.85, in excellent agreement with the results quoted in literature for the low-luminosity AGNs (Simpson 2005; Lu et al. 2010). For the tilt angle between stellar disk and torus plane, the effective tilt angle ΔTS,m = 37° corresponds to a mean tilt angle ΔTS ≈ 30°. We emphasis here that our assumption of the Gaussian distribution of cos ΔTS is in an arbitrary way, however, the mean tilt angle ($ΔTS ≈ 30°$) is quite robust and independent of the shape of the ΔTS distribution.

We show the 68% ($Δχ^2 = 2.30$) and 90% ($Δχ^2 = 4.61$) of the confidence levels of our model parameters in the sub-panel of Figure 3. As we can see, the parameter ΘT is degenerated with ΔTS,m to a certain extent. The effect of increasing the torus opening angle ΘT is similar to the increasing of the effective tilt angle ΔTS,m, which both result in a more randomized viewing angles of the disks of AGN hosts. Therefore, an independent measurement of ΘT from the type 2 AGN fraction is crucial to constrain the tilt angle ΔTS in our model.

4.2. The Obscuer: Stellar Dust Model

In this section, we test the scenario that the overdensity of the edge-on galaxies of type 2 AGNs is caused by an extra dust layer
aligned with the stellar disk. Therefore, we no longer assume that the nuclear obscurer is aligned with the stellar disk as it is in the aligned torus model (Section 4.1), but consider it as being randomly oriented. Besides the random orientated torus, the dust aligned with the stellar disk will obscure the nucleus when it is viewed as edge-on.

Using the denotations as in the aligned torus model, a randomly oriented nuclear torus means that the orientations of the stellar disk and torus plane are independent of each other, i.e., $\cos(\Delta T S)$ follows a distribution between 0 and 1. For its opening angle, we set $\Theta_T = 45^\circ$, the lower limit of the aligned torus model, since we have an extra component of type 2 AGNs obscured by the host-aligned dust layer. For a host-aligned obscurer, we assume that its height is the same as the stellar disk. Thus, for a stellar disk with height $\gamma$, its nucleus will be obscured when its viewing angles satisfies $\tan(\gamma) < \gamma$.

We then combine these two types of obscurers and get the final type 2 AGN sample. The other model settings and procedures are the same as in the aligned torus model. We show the model prediction as the dashed line in Figure 3. As we can see, this extra stellar obscurer model indeed predicts overdensity of the low axis ratio galaxies for the AGN sample. However, this overdensity mostly takes place at $b/a < 0.4$. For the others with $b/a > 0.4$, the predicted $N_{AGN}/N_{GAL}$ is almost a constant, whereas the observations show a continuous decrease of type 2 AGNs in more round galaxies. This is because most of the stellar disks have $\gamma < 0.4$ (see Figure 1). Therefore, this model prediction shows significantly poorer fitting ($\chi^2 \approx 36$, outside the 99.9% confidence interval of the $\chi^2$ distribution with eight freedoms) than the aligned torus model.

However, we would mention that there is no tuneable parameter in this stellar dust model, whereas the aligned torus model has two free parameters. Setting $\Theta_T$ to be a free parameter in the stellar dust model does not help, because the torus was assumed to be orientated randomly. However, assuming that the stellar dust layer follows the same shape of the stars might be too simplistic. A more sophisticated treatment of the distribution of the stellar dust might improve the fit (e.g., Maiolino & Rieke 1995), but is outside of the scope of this study.

5. CONCLUSION AND DISCUSSION

In this study, we select a sample of type 2 AGNs hosted by spiral galaxies from the DR7 of the SDSS. We build a control sample of non-active galaxies to the AGN sample by matching their observational and physical properties in detail. By comparing with the control sample, we find that the AGN hosts are systematically biased to edge-on views. By modeling the height and ellipticity of the disk galaxies with a non-parametric technique, we further find that this systematical bias cannot be quantified by an extra dust layer aligned with the stellar disk but can be nicely reproduced by assuming an average tilt angle of $\sim 30^\circ$ between the torus plane and stellar disk.

Some of the assumptions in our model are simplified, e.g., the constant type 2 AGN fraction. There are studies suggesting that the opening angle of the torus is correlated with the central AGN luminosity. For high luminosity AGNs, the distance of the torus from the nucleus is further (“receding torus model”) so that the torus opening angle and the type 2 AGN fraction $f_2$ are smaller (Lawrence 1991). Most of our AGNs are low luminosity objects ($L_{[OIII]} < 10^8 L_\odot$), and the type 2 AGN fraction has been shown to be roughly a constant in this luminosity region (Simpson 2005; Lu et al. 2010). A separation of our sample into two sub-samples according to $L_{[OIII]}$ also would not show any significant differences but reduce the goodness of the statistics. In the unified AGN diagram, the torus lies on the same plane of the accretion disk. In this case, the mean tilt angle between the torus plane and the stellar disk constrained from our model could also be understood as the mean tilt between the accretion disk and stellar disk.

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