A Single Intrinsic Luminosity Function for Both Type-I and Type-II Active Galactic Nuclei

Shuang Nan Zhang\textsuperscript{1,2,3,4}

\textsuperscript{1}Physics Department and Center for Astrophysics, Tsinghua University, Beijing, 100084, China (zhangsn@tsinghua.edu.cn)

\textsuperscript{2}Physics Department, University of Alabama in Huntsville, Huntsville, AL35899, USA (zhangsn@uah.edu)

\textsuperscript{3}Space Science Laboratory, NASA Marshall Space Flight Center, SD50, Huntsville, AL35812, USA

\textsuperscript{4}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

ABSTRACT

The luminous electromagnetic emission from distant active galactic nuclei (AGNs) including quasars is believed to be powered by accretion onto supermassive black holes (SMBHs). In the standard unification model for AGNs a dusty torus covers a significant portion of the viewing angles to the accretion disk and the BH. The system is classified as a type-I AGN if the accretion disk is viewed through the opening part; otherwise it is called a type-II AGN. Therefore the ratio of type-II to type-I AGNs serves as a sensitive probe to the unification model. A surprising discovery made from several large sky coverage and/or deep AGN surveys has found a significant anti-correlation between the type-II fraction and the observed X-ray luminosity between 2-10 keV. This suggests two different luminosity functions for the two types of AGNs, thus challenging the AGN unification model. However this observed anti-correlation is a natural consequence of the AGN unification model with only one intrinsic luminosity function if the inclination angle effects of the X-ray emitting accretion disk are taken into account. Thus the AGN unification model survived another critical test.

\textit{Subject headings:} galaxies: active, fundamental parameters (classification), luminosity function, Seyfert
1. Introduction

Observationally type-I AGNs are seen to have soft X-ray spectra (below about 10 keV) and both narrow and broad emission lines in their optical spectra, in contrast to type-II AGNs with harder X-ray spectra and only narrow optical emission lines (Antonucci 1993). These observations are naturally explained in the standard unification model of AGNs (Antonucci 1993) in which both the X-ray emission and the broad emission lines are produced within the region very close to the BH; the dusty torus blocks this region when viewed nearly edge-on (type-II AGNs) to the dusty torus. Because the dusty torus absorbs the broad optical emission lines almost completely and X-ray photons with lower energies suffer more absorption than higher energy photons, the type-II AGNs are observed to have harder X-ray spectra and do not show obvious broad optical emissions lines. Evidence has been accumulated from many different observations in infrared, optical and X-ray bands in support of this unification model for the two types of AGNs (Antonucci 1993). Despite of these progresses, no physically consistent model is currently available to account for the formation and evolution of the dusty torus, which may provide the crucial link between the galactic structure at larger scales and the accretion disk which fuels the SMBHs.

2. Correlation between X-ray luminosity and type-II AGN fraction

Recently it has been found that the torus structure may be different for AGNs with different X-ray luminosity, because the fraction of type-II AGNs is anti-correlated with the observed X-ray luminosity, e.g., found from combined ASCA, HEAO1 and Chandra surveys (Ueda et al. 2003), from combined Chandra and XMM-Newton surveys (Hasinger 2003), from combined ASCA and Chandra surveys (Steffen et al. 2003), from RXTE slew survey (Sazonov & Revnivtsev 2004), and from a sample of PG AGNs (Wang & Zhang 2004). Therefore the above unification scheme may need modifications. It is proposed that the smaller type-II fraction for more X-ray luminous AGNs may imply that the X-ray radiation is blowing out the dusty torus, such that the opening angles for more luminous AGNs become larger (Ueda et al. 2003; Hasinger 2003; Barger et al. 2005). However the dusty torus may also evolve by itself due to the dissipations of collisions among the clouds inside the torus (Krolik & Begelman 1988; Wang 2004). Despite of these progresses, the formation and evolution of the dusty torus, which may have important consequences for the formation and evolution of SMBHs and their host galaxies, are still poorly understood.

However the observed anti-correlation between type-II AGN fractions and X-ray luminosity may be naturally explained within the standard AGN unification model if the planes of the accretion disk and the torus are co-aligned and the X-ray emission is produced mainly
from the optically thick accretion disk. In this case, type-II AGNs are viewed nearly edge-on to both the torus and the accretion disk. Because a smaller X-ray flux is observed from an edge-on disk due to the less projected area of the disk, type-II AGNs appear to be less luminous than type-I AGNs for the same intrinsic luminosity. The observed apparent X-ray luminosity is reduced by a factor of \( \cos(\theta)(1 + 2 \cos(\theta))/3 \), where \( \theta \) is the inclination angle of the accretion disk and \( \theta = 90 \) degrees for an edge-on disk; the factor of \( \cos(\theta) \) is due to the area-projection effect and the factor of \((1 + 2 \cos(\theta))/3\) is due to the limb-darkening effect (Netzer 1987) respectively (though our calculations show the simple projection effect alone would produce almost identical results). If AGNs are assumed being oriented randomly in the sky, then the probability of seeing an AGN at an inclination angle \( \theta \) is proportional to \( \sin(\theta) \). Therefore for a given intrinsic luminosity of a group of AGNs, the observed apparent luminosity follows a distribution proportional to \( f(x) = \sqrt{1 - x^2}(1 + 2\sqrt{1 - x^2}) \), where \( x = \sin(\theta) \) is uniformly distributed between 0 and 1. Here we ignore all possible inclination angle dependent relativistic effects which may change both the observed X-ray flux and spectral shape if the emission region is close to the BH (Zhang Cui & Chen 1997), because the present AGN statistics does not require further refinement to this simple model. Consequently the convolution between \( f(x) \) and a given intrinsic luminosity function produces the observed apparent luminosity function, as shown in Figure 1.

In Figure 1, we apply the above mentioned simple inclination angle effects to the AGNs sample used by Ueda et al. (2003); all data points are from Figure 4 of Ueda et al. (2003). A simple broken-power law form of the intrinsic AGN luminosity function is first assumed, in order to mimic the overall features of the observed apparent luminosity function. We then convolve between \( f(x) \) and this intrinsic luminosity function to produce a trial apparent luminosity function. By adjusting the parameters of the assumed intrinsic luminosity function and compare each trial apparent luminosity function, the best estimates for these parameters are determined: \( N \propto L_X^{\alpha} \), where \( L_X \) is in units of erg/s, \( \alpha = 0.25 \) for \( 10^{42.75} < L_X \leq 10^{44.9} \) and \( \alpha = -0.7 \) for \( 10^{44.9} < L_X < 10^{47} \). It is clear that the observed apparent X-ray luminosity function (after absorption corrections) is significantly different from the assumed simple intrinsic luminosity form. If AGNs with inclination angles greater than 68 degrees are classified as type-II AGNs, we also show the predicted apparent luminosity functions for both type-I and type-II AGNs; clearly these two luminosity functions are also drastically different from each other.

In Figure 2, our model predicted type-II fraction as function of the observed apparent X-ray luminosity is compared to the observed anti-correlation. The data points are taken from Ueda et al. (2003) (Figure 4) and Hasinger (2003) (Figure 6, left panel), as indicated in Figure 2. The model predicted type-II AGN fraction is calculated as the ratio between the predicted apparent type-II AGN luminosity function and the observed apparent total
Fig. 1.— AGN luminosity function. The intrinsic luminosity function, referred to as the AGN luminosity before correcting for the inclination angle effects, is assumed of a broken power-law shape, i.e., $N \propto L_X^\alpha$, where $L_X$ is in units of erg/s, $\alpha = 0.25$ for $10^{42.75} < L_X \leq 10^{44.9}$ and $\alpha = -0.7$ for $10^{44.9} < L_X < 10^{47}$; these parameters are determined by matching the data with the model predictions. The observed luminosity distribution (after absorption corrections) of AGNs (Ueda et al. 2003) agree with the predicted apparent luminosity defined as $L_X = F_X 4\pi D_L^2$, where $F_X$ is the observed X-ray flux and $D_L$ is the luminosity distance of the AGN. The predicted type-I and type-II AGN luminosity functions are also shown for comparison, if AGNs with inclination angles greater than 68 degrees are classified as type-II AGNs. Clearly in the low luminosity range type-II AGNs dominates, in contrast to the high luminosity range where one finds mostly type-I AGNs.
Fig. 2.— Type-II AGN fraction as function of the observed apparent X-ray luminosity (after absorption corrections). The data points shown by diamonds and triangles are shifted horizontally by 0.05 and -0.05 respectively for displaying clarity. Because the three different groups of type-II AGNs, i.e., optical and X-ray type-II AGNs from Ueda et al. (2003) and X-ray type-II AGNs from Hasinger (2003) may have slightly different definitions in terms of the dividing inclination angle between type-I and type-II AGNs, we also show two different model predictions corresponding to two critical inclination angles of 68 and 76 degrees respectively. We did not include the model-fitted relation between type-II AGN fraction and X-ray luminosity by Ueda et al. (2003) because the relation contains only three values over the entire luminosity range, lacking details for comparison to our model predictions with several distinctive features; the general trend of the three values is not significantly different from the “raw” data points shown here.
luminosity function, as shown in Figure 1. Because different samples of type-II AGNs may have different dividing inclination angles, we show our model predictions for two different dividing inclination angles of 68 and 76 degrees respectively. Not only our model re-produces the observed overall tendency of the anti-correlation, several features of the observed anti-correlation also agree with the model predictions well (albeit the limited statistics in the data), e.g., the rapidly declining region for $10^{44} < L_X < 10^{44.5}$ and the two slowly declining segments between $10^{42.5} < L_X < 10^{44}$ and $10^{45.5} < L_X < 10^{46}$. Comparing with the observed type-II fractions, the dusty torus opening angle is inferred as around 70 degrees, in agreement with the range of inclination angles determined for some Seyfert-I AGNs (Wu & Han 2001). The predicted nearly 100% type-II AGNs for $L_X < 10^{42}$ is the direct consequence of the intrinsic luminosity function cutoff below $10^{42.75}$ erg/s. Similarly the predicted rapid decreases of type-II AGNs for $10^{44} < L_X < 10^{44.5}$ and $L_X > 10^{46}$ are due to the intrinsic luminosity function break and cutoff at $L_X \sim 10^{45}$ and $L_X > 10^{46}$ respectively. Future AGN surveys with more statistics for both low and high luminosity ends will test the predictions of our model and thus measure the intrinsic AGN luminosity function more accurately.

3. Discussion and conclusion

We first stress the point that because of the inclination angle effects, the observed apparent luminosity of each AGN is not the intrinsic luminosity of the AGN, unless the inclination angle of each AGN is measured directly and the inclination angle effects are corrected to recover the intrinsic luminosity for each AGN. Lacking of inclination angle information for most AGNs, the intrinsic luminosity function of AGNs is currently not observed directly, because the observed apparent luminosity function is already convolved with the inclination angle effects. We therefore assumed a simple broken-power law form of the intrinsic luminosity function and determined the parameter values by fitting the convolved luminosity function (with $f(x)$) with the observed apparent luminosity function. The functional form is not motivated astrophysically, but simply chosen to obtain a good fit with the observed apparent luminosity function with a minimum number of free parameters. The good agreement between this simple form of intrinsic luminosity function suggests that any reasonable AGN synthesis model should be able to re-produce AGN intrinsic luminosity function similar to that shown in Figure 1.

In this AGN unification model, we explicitly require that the X-ray emission is mainly produced from an optically thick accretion disk coaxed with the torus. For the typical type-I AGN NGC 4151, its hard X-ray power-law exhibits a characteristic cutoff above around 50 keV, which may be explained as due thermal Comptonization of cold disk pho-
tons in a hot medium (Zdziarski et al. 2002). Detailed modeling of the hard X-ray spectrum resulted in a Comptonization $y$-parameter of $0.88^{+0.12}_{-0.11}$ and an electron temperature of $73^{+34}_{-29}$ (Zdziarski et al. 2002), i.e., the Compton scattering optical depth is 0.93-2.9, supporting our optically thick assumption of the scattering medium.

Many observations are also consistent with the disk origin of AGN X-ray emission. For example, the comparison between the variabilities in the X-ray light curves of AGNs, intermediate mass BH systems and X-ray BH binaries shows that the variability timescales are proportional to their BH masses (Edelson & Nandra 1999; Lee et al. 2000; Vaughan Fabian & Nandra 2003; Strohmayer & Mushotzky 2003; Markowitz et al. 2003; Cropper et al. 2004). This demonstrates the same accretion disk origin of X-ray radiation from all these systems, and thus similar physical processes may be going on in astrophysical systems with entirely different scales (Zhang et al. 2000). In particular for the SMBH in the center of the milky way, several disk oscillation modes are identified from its X-ray flares (Baganoff et al. 2001) which allowed very precise estimate of the mass and angular momentum of the BH (Aschenbach et al. 2004). The inverse Compton scattering process in the accretion disk may be responsible for the observed X-ray emission (Liu & Melia 2002). Alternatively magnetic energy release may be responsible for X-ray emissions from the solar and stellar coronae, and accretion disks in X-ray binaries, intermediate mass and SMBHs, because in all these systems X-ray flares are commonly seen (Liu & Li 2004). A disk-like patchy corona (Haardt Maraschi & Ghisellini 1994) in AGN disk may produce the observed power-law like X-ray emission through magnetic reconnection process (Wang Watarai & Mineshige 2004). Socrates, Davis & Blaes (2004) have pointed out recently that in the innermost regions of radiation pressure supported accretion disks around black holes in both stellar mass and supermassive black holes, the turbulent magnetic pressure may greatly exceed the gas pressure. Consequently turbulent Comptonization may be able to produce X-ray photons in these accretion disks independent of the central black hole mass, providing a viable mechanism for X-ray photon production in AGN disks.

The assumption of the disk-torus alignment, as assumed previously (Wu & Han 2001), is also natural. The formation of an accretion disk requires significant amount of angular momentum for the material transferred to the disk at larger radii. The only known structure in an AGN immediately outside the accretion disk is the dusty torus. Therefore the accretion disk and the torus should be aligned if the torus is the source of the material forming the accretion disk (Krolik & Begelman 1988).

We conclude that the AGN unification proposed about two decades ago has survived another critical test. The success of our simple model, in predicting the observed apparent X-ray luminosity of AGNs and the type-II AGN fractions, calls for a unification model for
AGNs including a torus, an X-ray emitting accretion disk and a central SMBH; we call this “TAXI” model, which stands for Torus of Antonucci with X-ray Inclination-angle effects. The inferred single intrinsic luminosity function for AGNs, which is significantly different from the observed apparent luminosity function, should be used in the future for all AGN population synthesis and related studies. Within the framework of this model, it is important to investigate further the physics for the formation of the torus and its relationship with the X-ray emitting accretion disk, in order to understand the formation and evolution of SMBHs and galaxies (Kauffmann & Haehnelt 2000; Page et al. 2001; Menci et al. 2004), which are intimately related to the properties of dark matter and the evolutionary history of the universe (Baes et al. 2003; Di Matteo et al. 2003).

Acknowledgement: The anonymous referee is appreciated for his/her comments and suggestions, which allowed us to clarify some issues and improve the presentation of the paper significantly. We thank Dr. Jian-Min Wang and Mr. Xin-Lin Zhou of IHEP/CAS (China) for interesting discussions and many helpful suggestions. We also thank the organizers and participants of the 2004 Annual IHEP-Tsinghua Student Astrophysics Symposium for many stimulating discussions, which motivated us for this work. NSFC, CAS and MOST in China and NASA in USA are acknowledged for partial financial support to SNZ through several research grants.

REFERENCES


