A SINGLE INTRINSIC LUMINOSITY FUNCTION FOR BOTH TYPE I AND TYPE II ACTIVE GALACTIC NUCLEI

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ABSTRACT

The luminous electromagnetic emission from distant active galactic nuclei (AGNs) including quasars is believed to be powered by accretion onto supermassive black holes. In the standard unification model for AGNs, a dusty torus covers a significant portion of the viewing angles to the accretion disk and the black hole. 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 is a significant anticorrelation between the type II fraction and the observed X-ray luminosity between 2 and 10 keV. This suggests two different luminosity functions for the two types of AGNs, thus challenging the AGN unification model. However, this observed anticorrelation 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.

Subject headings: galaxies: active — galaxies: fundamental parameters — galaxies: luminosity function, mass function — galaxies: Seyfert

1. INTRODUCTION

Observationally, type I active galactic nuclei (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 black hole (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 emission 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 this progress, 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 that fuels the supermassive black holes (SMBHs).

2. CORRELATION BETWEEN THE X-RAY LUMINOSITY AND THE 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 anticorrelated with the observed X-ray luminosity, e.g., found from combined ASCA, HEAO 1, and Chandra surveys (Ueda et al. 2003), from combined Chandra and XMM-Newton surveys (Hasinger 2004), from combined ASCA and Chandra surveys (Steffen et al. 2003), from the Rossi X-Ray Timing Explorer 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-radiation is blowing out the dusty torus, such that the opening angles for more luminous AGNs become larger (Ueda et al. 2003; Hasinger 2004; Barger et al. 2005). However, the dusty torus may also evolve by itself owing to the dissipations of collisions among the clouds inside the torus (Krolik & Begelman 1988; Wang 2004). Despite this progress, 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 anticorrelation 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 owing 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 \( \frac{1}{2} \cos \theta \) 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; although our calculations show the simple projection effect alone would produce almost identical results). If AGNs are assumed to be 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 \( f(x) = (1 - x^2)^{1/2}[1 + 2(1 - x^2)^{1/2}] \), 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 et al. 1997), because the present AGN statistics do 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 AGN 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 comparing each trial apparent luminosity function, the best estimates for these parameters are determined: \( N \propto L_x \), where \( L_x \) is in units of ergs per second, \( \alpha = 0.25 \) for \( 10^{44.5} < L_x \leq 10^{44.9} \), 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 \( L_a = f_a D_L \), where \( f_a \) 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° are classified as type II AGNs. Clearly, in the low-luminosity range, type II AGNs dominate, in contrast to the high-luminosity range, where one finds mostly type I AGNs.

In Figure 2, our model-predicted type II 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 (2004), 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°, respectively. We did not include the model-fitted relation between the type II AGN fraction and the 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.

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. Because we lack the 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 reproduce an 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 to thermal Comptonization of cold disk photons 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 $73^{+34}_{-26}$ keV (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 et al. 2003; Strohmayer & Mushotzky 2003; Markowitz et al. 2003; Cropper et al. 2004). This demonstrates the same accretion disk origin of X-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 a 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 BHs, and SMBHs, because in all these systems X-ray flares are commonly seen (Liu & Li 2004). A disklike patchy corona (Haardt et al. 1994) in AGN disks may produce the observed power-law–like X-ray emission through a magnetic reconnection process (Wang et al. 2004). Socrates et al. (2004) have pointed out recently that in the innermost regions of radiation pressure–supported accretion disks around both stellar mass BHs and SMBHs, 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 BH 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 a 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 model 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 the “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).

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