Relativistic Effects on the Observed AGN Luminosity Distribution

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Abstract

Recently Zhang (2005) has proposed a model to account for the well established effect that the fraction of type-II AGNs is anti-correlated with the observed X-ray luminosity; the model consists of an X-ray emitting accretion disk coaligned to the dusty torus within the standard AGN unification model. In this paper the model is refined by including relativistic effects of the observed X-ray radiations from the vicinity of the supermassive black hole in an AGN. The relativistic corrections improve the combined fitting results of the observed luminosity distribution and the type-II AGN fraction, though the improvement is not significant. The type-II AGN fraction prefers non- or mildly spinning black hole cases and rules out the extremely spinning case.

Key words: galaxies: Seyfert - galaxies: active - galaxies: luminosity function - radiation mechanisms: non-thermal - X-rays: general
1. Introduction

It is well known that Seyfert Galaxies can be classified as Seyfert I and Seyfert II. Seyfert I galaxies have both narrow and broad emission lines in their optical spectra, while Seyfert II galaxies only have narrow optical emission lines. In the unified model of Seyfert galaxies (Antonucci 1993), this distinction is due to the different inclination of our line of sight with respect to an obscuring torus surrounding the source (Veron-Cetty & Veron 2000). Therefore, it is expected that the observed luminosity distribution of these two types should be identical except for the effects of obscuration by the torus material. However, in several recent X-ray surveys of AGN (Ueda et al. 2003; Hasinger 2004; Steffen et al. 2003) it has been found that the fraction of type-II AGNs is anti-correlated with the observed X-ray luminosity, such that the luminosity dependent dusty torus model may be required. However, this observed anti-correlation could be explained in the framework of unified model if the inclination angle effects of X-ray radiation are taken into account (Zhang 2005, hereafter Z05). It was pointed by Nayakshin (2006) recently that the X-ray emission continuum of an accretion disk should be anisotropic, if the emission is composed of moderately optically thick magnetic flares (Zhang 2006). Nayakshin (2006) further used this model to explain the well known observations that the X-ray continuum and reflected component off the accretion disk are not well correlated (Markowitz et al. 2003). For simplicity and focusing on the inclination angle effects, relativistic effects produced when the X-ray is emitted in accretion disk are ignored in Z05. However, the relativistic effects certainly exist when the emission region is close to the black hole. We will consider relativistic corrections to the observed luminosity distributions and the type-II AGN fraction in §2. In this section, we utilize the combined fitting of the observed luminosity distribution and the type-II AGN fraction to constrain the spin of supermassive black holes in the sample. Perhaps both the luminosity dependent dusty torus model and the above effects operate simultaneously. In this paper we focus on the effects of inclination angle and relativistic effects, demonstrating that these effects are also important. In §3 we show our conclusion and make some discussion.
2. AGN Luminosity Distribution with Relativistic Corrections

If we consider the inclination angle effects, the type II AGNs viewed nearly edge-on appear to be less luminous than type I AGNs viewed nearly face-on for the same intrinsic luminosity. This is due to the less projected area of the accretion disk, when we observe it with an inclination angle. Therefore, in the non-relativistic case when we view an AGN system with an inclination angle \( \theta \), defined as the angle between the normal direction of the accretion disk (also the spin axis of the black hole) and the line of sight, the observed luminosity will be reduced by a factor of \( \cos \theta \) compared with the face-on case, i.e., \( \theta = 0^\circ \). This projection factor will become complicated after considering the relativity correction, as shown in figure 1. If the limb-darkening effect (Phillips & Meszaros 1986) is considered, an additional factor of \( (1 + 2 \cos \theta)/3 \) to the observed luminosity will be included (Netzer 1987). We assume the orientation of AGNs is isotropic. Therefore, the probability density of \( \theta \) is \( \sin \theta (0 < \theta < \pi/2) \).

With the relation between the flux (i.e., the luminosity) and \( \theta \) (figure 1), we could obtain the probability of the observed luminosity, i.e. \( f(L) \), for a given intrinsic luminosity numerically. Then the observed luminosity distribution is the convolution between \( f(L) \) and the intrinsic luminosity distribution.

The relativistic effects include the Doppler shift and boosting, the gravitational redshift and light bending. The correction is calculated by the ray-tracing method (Fanton et al. 1997). Li et al. (2005, hereafter L05) have improved the method by including the effect of returning radiation and allowing a nonzero torque to be set at the inner edge of the disk. However, the improvement is not significant when the free parameter \( \eta \) (see L05) is less than 0.3. Actually, \( \eta \) was set to be 0 when the spectra were fitted by the model in L05. We adopt the standard Keplerian optically thick and geometrically thin disk (Shakura & Sunyaev 1973). We assume the disk lies on the equatorial plane of a Kerr black hole, and the inner edge of the disk is the last stable orbit and outer edge is \( 200r_g \) (beyond this radius the X-ray radiation is negligible), where \( r_g \) is the gravitational radius of the black hole. For the local spectrum, it contains two components, a multi-color disk spectrum in all energy bands and a power law only in 2-10 keV band. The temperature profile of the blackbody-like component is derived on the Kerr metric (Thorne 1974). However, the temperature of the disk of Seyfert galaxies is only 50-100 eV or less, so the blackbody-like component is secondary in the energy range 2-10 keV concerned; we only use its radiation power to control the distribution of the power law component. If we assume the total radiation powers of the two components are equal, then the proportionality of the two components is about \( 10^5 \) in 2-10 keV band. We assume the value of the proportionality is 1000 in our calculation, because the results of luminosity distributions and spectral shapes are not sensitive to larger values of proportionality of the two components. The spectral index is assumed to have a form \( \alpha = -0.45 + (r/r_g)^{1/4}/1.2 \), in order to mimic the shape of the observed power law after the relativistic corrections. We stress that this spectral model is
Fig. 1. The observed X-ray flux and inclination angle dependence for non-relativistic and relativistic cases in 2-10 keV. The shape strongly depends on the energy range and the spin of black hole (Zhang, X. L., et al. 2004). The flux decreases with the value of spin increasing for the face-on cases, since the gravitational redshift and transverse Doppler shift (also redshift) become more significant for high spinning cases. In contrast the bump for the large inclination angle and high spinning cases is due to the effects of Doppler beaming and gravitational focusing (especially for the high energy band concerned here, also see L05).

only phenomenological, because currently no self-consistent physical model of accretion disk emission (because the nature of the inferred X-ray emitting “corona” is currently unknown and remains a controversial issue) is available to account for the observed AGN X-ray spectra in details, without invoking some kind of assumptions and/or parameterizations. However, our main results about the total flux are not sensitive to the exact form of the phenomenological model used here, because our main goal is to re-produce the observed X-ray spectra, which is of course also the goal of any physically self-consistent accretion disk emission model.

The intrinsic luminosity distribution, referred to as the AGN luminosity before correcting for the inclination angle effect and relativistic 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 \( 10^{42.75+x} < L_X \leq 10^{44.9+x} \) and \( \alpha = -0.7 \) for \( 10^{44.9+x} < L_X < 10^{47+x} \); these parameters are determined by matching the data with the model predictions (Z05). The parameter \( x \) is changed for different cases to obtain the best agreement (i.e. the minimum \( \chi^2 \) values) with the data. We use luminosity distribution instead of luminosity function which is usually used in studying AGN. Indeed given the instrument sensitivity and sky exposure, the luminosity distribution can be derived uniquely
from any assumed luminosity function. Our goal is to understand the effects of inclination angle and relativistic effects to the observed luminosity of AGNs, rather than attempting to understand the physical origin of the intrinsic luminosity function. Therefore, we may study either luminosity function or luminosity distribution. Since complex modeling is required to obtain the AGN luminosity function, but the luminosity distribution is obtained directly from data, we choose to focus our study on luminosity distribution, in order to understand the effects of inclination angle and relativistic effects to the observed luminosity of AGNs.

We fit the observed luminosity distribution and the type-II AGN fraction at the same time in order to distinguish between different models. The total $\chi^2_{\text{total}}$ is defined as $\chi^2_L + \chi^2_F$, in which $\chi^2_L$ and $\chi^2_F$ are obtained with the observed luminosity distribution and the type-II AGN fraction respectively. The minimum value of $\chi^2_{\text{total}}$ for non-relativistic case is 38.17 ($x = -0.01^{+0.06}_{-0.05}$, the dividing inclination angle between type II and type I AGNs, $\theta_c = 65.5^{+1.5}_{-1.0}$°, the degree of freedom is 30, i.e. DOF=30); for the relativistic case, the minimum value of $\chi^2_{\text{total}}$ is obtained when $a^* = 0.01$ ($\chi^2 = 35.69$, $x = -0.03^{+0.04}_{-0.03}$, $\theta_c = 66.5^{+1.5}_{-1.0}$°, DOF=29). Although the results of the relativistic case are better than the non-relativistic case, the improvement is not significant. The significance of improvement given by F-test is 83.4%. We show the results of the observed luminosity distribution and the type-II AGN fraction in figure 2 and 3 respectively. With the fitting result, we could determine the upper limits of $a^*$ are 0.46, 0.69 and 0.87 corresponding to 1, 2 and 3σ, respectively (figure 4). For the extremely spinning case ($a^*=0.998$), the minimum value of $\chi^2_F$ is 54.02 ($x = 0.27$, $\theta_c = 68.0$°), corresponding to a probability less than $10^{-10}$. On the other hand, the upper limit of $a^*$ determined by $\chi^2$ statistic is 0.75 with 90% confidence, which is consistent with the results above.

In summary, the combined fitting result of the observed luminosity distribution and the type-II AGN fraction favors non- or mildly spinning black hole cases; the extremely spinning case is ruled out with high confidence. The dividing inclination angle between type II and type I AGNs is between 60 and 70 degrees, slightly different from that of 68 and 76 degrees in Z05 and in slightly better agreement with the range of inclination angles of type I AGNs determined by Wu & Han (2001).

3. Conclusion and Discussion

The main results of this paper are: (1) The relativistic corrections improve the combined fitting results of the observed luminosity distribution and the type-II AGN fraction, though the improvement is not very significant. (2) The fitting results prefer non- or mildly spinning black hole cases, and the extremely spinning case is ruled out with high confidence.

The result of type-II AGN fraction shows that the majority of black holes in the sample cannot be extremely spinning, especially for the high luminosity ones (as shown in figure 3). Several authors have investigated the spin of supermassive black holes in AGNs in both theoretical and observational aspects. A considerable fraction of high luminosity AGNs in the
Fig. 2. The predicted AGN luminosity distributions for non-relativistic and $a^* = 0.01$ cases (2-10 keV). The observed luminosity distribution (after absorption corrections) of AGNs (Ueda et al. 2003) agrees with the predicted apparent (observed) luminosity defined as $L_X = F_X 4\pi D_L^2$, where $F_X$ is the observed X-ray flux after absorption corrections and $D_L$ is the luminosity distance of the AGN.

sample in Ueda et al. (2003) and Hasinger (2004) are high redshift QSOs ($z = 1 \sim 3$). For the QSOs, some recent calculations about the evolution of the spin of supermassive black holes (Shapiro 2005; Volonteri et al. 2005) find that most black holes are rapidly spinning by $z \sim 5$. In their calculations, the accretion rates have been set equal to the Eddington accretion rate all the time. We have also investigated how the evolution of accretion rate impacts the evolution of the spin of supermassive black holes. We have found that the spin of black hole should have approached the maximum value before the accretion rate has declined significantly after the QSO formation, which is most likely a merger event (Yu et al. 2005). It is therefore clear that black holes should become extremely spinning in the QSO stage very rapidly, provided that there are not other mechanisms that could reduce the spin. However, extraction of black hole’s spin energy is believed to be the main mechanism in powering relativistic jets from supermassive black holes and thus preventing it from becoming rapidly spinning in the QSO stage (Koide et al. 2002). In fact it is highly possible that QSOs may lose their spin energy very rapidly, so that their black holes only remain in the highly spinning state shortly, i.e., the high accretion rate stage, agreeing with the fact that most QSOs are radio quiet. In addition, the supermassive black holes could grow up while keeping the spin low by chaotic accretion (King & Pringle 2006). As a result of the above possible mechanisms, the average spin of QSOs is
Fig. 3. Type-II AGN fraction as function of the observed apparent X-ray luminosity (after absorption corrections) for non-relativistic, $a^* = 0.01$ and 0.998 cases. 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. As shown in this figure, the $a^* = 0.998$ case cannot produce the decreasing trend of type-II AGN fraction in the high luminosity band ($L_X > 10^{43.5}$ erg/s).

likely to be only moderate. For Seyfert galaxies, if they have not undergone a merger event recently (Grogin et al. 2005) and then maintained low accretion rate, their spin could also be low or mild.

The spin of a black hole can also be inferred from the radiation efficiency. The radiation efficiencies corresponding to the 1, 2 and 3σ upper limit of the spin deduced from our results are about 8%, 10% and 15%, respectively. Yu & Tremaine (2002) found $\eta \geq 0.1$ of optical selected quasar, while the results from the cosmic X-ray background indicate $\eta \geq 0.15$ (Elvis et al. 2002). Higher values of $\eta$ (about 30%-35%) have been obtained by Wang et al. (2006) from a large sample of quasars selected from the Sloan Digital Sky Survey. However, it may be reduced by a factor $\sim 2$ due to the uncertainty of the black hole mass (Wang et al. 2006). Therefore, our results are not in conflict with these previous results, but instead provide useful constraints.

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Fig. 4. The $\chi^2$ curve by fitting the observed luminosity distribution and the type-II AGN fraction as function of apparent X-ray luminosity. Both $x$ and $\theta_c$ are also adjusted to obtain the minimum $\chi^2_{\text{total}}$ for each value of $a^*$. 

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References

Antonucci R. 1993, ARA&A, 31, 473
Elvis, M., Risaliti, G., & Zamorani, G. 2002, ApJ, 565, L75
Fanton, C. et al. 1997, PASJ, 49, 159
Grogin, N. A. et al. 2005, ApJ, 627, L97
Hasinger, G. 2004, Nucl. Phys. B Proc. Suppl., 132, 86
King, A. R., & Pringle, J. E. 2006, MNRAS, in press (astro-ph/0609598)
Koide, S. et al. 2002, Science, 295, 1688
Li, L. X. et al., 2005, ApJS, 157, 335
Markowitz, A., Edelson, R., & Vaughan S., 2003, ApJ, 598, 935
Nayakshin, S. 2006, submitted to MNRAS Letters (astro-ph/0611347)
Netzer, H. 1987, MNRAS, 225, 55
Phillips, K. C., & Meszaros, P. 1986, ApJ, 310, 284
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shapiro, S. L. 2005, ApJ, 620, 59
Steffen, A. T., Barger, A. J., Cowie, L. L., Mushotzky, R. F., & Yang, Y. 2003, ApJ, 596, L23
Thorne, K. S. 1974, ApJ, 191, 507
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886
van Putten, M.H.P.M., & Levinson, A. 2002, Science, 295, 1874
Veron-Cetty, M. P., & Veron, P. 2000, A&ARv, 10, 81
Volonteri, M. et al. 2005, ApJ, 620, 69
Wang, J. M. et al. 2006, ApJ, 642, L111
Wu, X., & Han, J. L. 2001, ApJ, 561, L59
Yu, Q., & Tremaine, S. 2002, MNRAS, 335, 965
Yu, Q., Lu, Y., & Kauffmann, G. 2005, ApJ, 634, 901
Zhang, S. N. 2005, ApJ, 618, L79 (Z05)
Zhang, S. N. 2006, Invited Discourse, the 26th IAU General Assembly, Prague, Czech Republic
Zhang, X. L., Zhang, S. N., Feng, Y. X., & Yao, Y. S. 2004, HEAD, 8.4001Z