CONSTRAINTS ON THE RADIATIVELY INEFFICIENT ACCRETION HISTORY OF ACTIVE GALACTIC NUCLEI FROM THE HARD COSMOLOGICAL X-RAY BACKGROUND

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ABSTRACT

The transition of a standard thin disk into a radiatively inefficient accretion flow (RIAF) is expected to occur when its accretion rate $\dot{m}$ is lower than a critical value $\dot{m}_{\text{crit}}$ ($\dot{m} = M/M_{\text{Edd}}$). RIAFs are very hot, and they radiate mostly in the hard X-ray band ($\gtrsim 100$ keV). Assuming that the accretion disk in every bright active galactic nucleus (AGN) will finally undergo an RIAF phase when $\dot{m} < \dot{m}_{\text{crit}}$, we calculate the contribution of the RIAFs in AGNs to the cosmological X-ray background at 10–1000 keV. We find that the timescale $t_{\text{RIAF}}$ of an RIAF accreting at $\dot{m} \lesssim \dot{m}_{\text{crit}}$ should be shorter than $\sim 10^{-3} t_{\text{p}}$ if $\dot{m}_{\text{crit}} = 0.01$, where $t_{\text{p}}$ is the lifetime of bright AGNs; that is, $\dot{m}$ declines from $\dot{m}_{\text{crit}}$ to a rate significantly lower than $\dot{m}_{\text{crit}}$ within $t_{\text{RIAF}}$. The derived timescale $t_{\text{RIAF}}$ is affected by the parameters adopted in the model calculations, which are also discussed.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — quasars: general — X-rays: diffuse background

1. INTRODUCTION

The AGN X-ray luminosity function (XLF) is directly linked to the accretion history of AGNs in the universe. Much work on XLFs has been carried out in the soft X-ray band ($\lesssim 3$ keV; e.g., Maccarone et al. 1991; Boyle et al. 1993; Page et al. 1997; Miyaji et al. 2000) and the hard X-ray band ($\gtrsim 2$ keV; e.g., Boyle et al. 1998; Cowie et al. 2003; Ueda et al. 2003). The luminosity functions (LFs) derived from surveys in the soft X-ray band ($\lesssim 3$ keV) may have missed many obscured (type II) AGNs, while the hard X-ray surveys ($\sim 2–10$ keV) can trace the whole AGN population, including obscured type II AGNs. The cosmological X-ray background (XRB) is most contributed by AGNs (Hasinger 1998; Schmidt et al. 1998). In the most popular synthesis models of the XRB based on the unification schemes for AGNs, the cosmological XRB from $\lesssim 2$ keV to more than several hundred keV can be fairly well reproduced by using a template spectrum for AGNs consisting of a power-law X-ray spectrum with an exponential cutoff around several hundred keV (see, e.g., Matt & Fabian 1994; Madau et al. 1994; Comastri et al. 1995; Gilli et al. 1999; Ueda et al. 2003). Di Matteo & Fabian (1997) have alternatively proposed that the very hard X-ray background (VHXRB; the term is used here for the hard X-ray background above 10 keV) may be dominated by the thermal bremsstrahlung emission from advection-dominated accretion flows (ADAFs) in low-luminosity AGNs. Further detailed ADAF spectral calculations (Di Matteo et al. 1999) have shown that many sources at redshift $z = 2–3$ with ADAFs accreting at rates close to the critical value are required to reproduce the observed VHXRB spectral shape. Recently, Ueda et al. (2003) derived a hard X-ray luminosity function (HXLF) from a highly complete AGN sample (2–10 keV), which includes both type I and type II AGNs (except Compton-thick AGNs). Based on this HXLF, their synthesis models can explain most of the observed XRB from the soft X-ray band to the hard X-ray band, around several hundred keV. Their calculations slightly ($\lesssim 10\%–20\%$) underestimate the relative shape of the XRB spectrum around its peak intensity (see Fig. 18 of Ueda et al. 2003). Such a discrepancy can be explained provided the same number of Compton-thick AGNs with log $N_H = 23–25$ as those with log $N_H = 23–24$ are included. This implies that the contribution to the VHXRB from radiatively inefficient accretion flows (RIAFs) in AGNs may be important, but not dominant, even if the contribution from Compton-thick AGNs is not considered.

There are a variety of studies exploring the evolution of AGNs based on optical quasar LFs, XLFs, or both (e.g., Haehnelt & Rees 1993; Haiman & Menou 2000; Kauffmann & Haehnelt 2000; Yu & Tremaine 2002; Wyithe & Loeb 2003; Marconi et al. 2004). A common conclusion is that the timescale of AGN activity is short compared with the Hubble timescale, though the quantitative results on the bright quasar lifetime vary from $\sim 10^7$ to $\sim 10^9$ yr for different investigations. The standard optically thick accretion disks are present in bright AGNs, provided the accretion rate is high. The AGN activity may be switched off when the gases near the black hole are exhausted (see Narayan 2002 for a recent review, and references therein). When the accretion rate $\dot{m} (= M/M_{\text{Edd}})$ declines below a critical value $\dot{m}_{\text{crit}}$, the standard disk converts to an RIAF (see, e.g., Narayan & Yi 1995). The RIAF is optically thin and very hot, and its spectrum is peaked at around several hundred keV. There is abundant observational evidence indicating that RIAFs are indeed present in many low-luminosity AGNs and in our Galactic center’s Sgr A* (e.g., Narayan & Yi 1995; Lasota et al. 1996; Gammie et al. 1999; Yuan & Narayan 2004).

In this Letter, we explore how the inefficient-accretion history of AGNs is constrained by the VHXRB. The cosmological parameters $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ have been adopted in this work.

2. MODEL

The HXLF given by Ueda et al. (2003) is so far the most suitable for our present investigation, as it includes both type I and type II AGNs (except Compton-thick AGNs). Assuming the accretion disk in every bright AGN will become an RIAF while its accretion rate is low, we derive the comoving space number density of these faint AGNs containing RIAFs from the HXLF, provided the accretion-rate evolution is known. Based on theoretical spectral calculations for RIAFs, strict con-
straints on the accretion history of AGNs can be achieved from a comparison with the cosmological VHXRB at 10–1000 keV.

2.1. Space Density of Faint AGNs

We assume that all AGNs described by the HXLF have standard accretion disks (we will come to justify this assumption in § 4). Hereafter, we refer to these AGNs with standard disks as “bright AGNs,” while those with RIAFs are “faint AGNs.” The X-ray luminosity in the 2–10 keV band can be converted to the bolometric luminosity by using an empirical relation:

\[ L_{\text{bol}} = f_{\text{cor}} L_X, \]

where \( f_{\text{cor}} = 100 \) is adopted (Elvis et al. 2002; Menci et al. 2004). The black hole mass density for bright AGNs in comoving space at redshift \( z \) can be calculated as

\[ \rho_{\text{bh}}(z) = \frac{f_{\text{cor}}}{m^\text{aver}} \int \frac{d\Phi(L_X, z)}{d \log L_X} d \log L_X M_{\odot} \text{Mpc}^{-3}, \]

(1)

where \( \Phi(L_X, z) \) is the HXLF given by Ueda et al. (2003), \( m^\text{aver} \) is the average dimensionless accretion rate for bright AGNs described by this HXLF, and \( L_{\text{bol}} \) is the Eddington luminosity for a black hole with solar mass.

In this Letter, we assume that the black hole mass does not change significantly after the accretion mode transition, which is satisfied only if we take the time after the transition to be shorter than the Salpeter timescale, because the accretion rates of these faint AGNs are very low (\( \dot{m} \ll 10^{-2} \)). The total monochromatic X-ray luminosity of all faint AGNs in units of comoving volume is given by

\[ L_{X}^{\text{faint}}(z) = \int n'(M_{\text{bh}}, z) dM_{\text{bh}} \times \int_{0}^{L_{X}^{\text{aver}}(M_{\text{bh}}, E)} \frac{1}{t'} \int \frac{dL_{X}(E, t)}{dt} L_{X}(E) dL_{X}(E), \]

(2)

where \( n'(M_{\text{bh}}, z) \) is the black hole mass function for faint AGNs and \( L_{X}^{\text{aver}}(M_{\text{bh}}, E) \) is the X-ray luminosity of an RIAF accreting at \( \dot{m} = m^\text{aver} \). For simplicity, we employ the conventionally adopted assumption of a fixed lifetime \( t' \) and the same light curve for all faint AGNs. For RIAFs in AGNs, the spectra \( L_{X}(E) \) depend almost linearly on the black hole mass \( M_{\text{bh}} \), and equation (2) can be rewritten as

\[ L_{X}^{\text{faint}}(E, z) = \frac{1}{t'} \int \frac{M_{\text{bh}}}{10^{8} M_{\odot}} n'(M_{\text{bh}}, z) dM_{\text{bh}} \int_{0}^{t'f} l_{X}(E, t) dt \]

\[ = \frac{1}{t'} \rho_{\text{bh}}(z) \int_{0}^{t'f} l_{X}(E, t) dt, \]

(3)

where \( l_{X}(E, t) \) is the faint-AGN light curve for a 10\(^8\) \( M_{\odot} \) black hole, which can be calculated provided the time-dependent accretion rate \( \dot{m}(t) \) is known. The total number density \( N(z) \) of faint AGNs is \( N(z) = N(z) t'/t'^8 \), where \( t'^8 \) is the lifetime of bright AGNs, and the bright AGN number density \( N(z) \) can be calculated from the HXLF. The black hole mass density \( \rho_{\text{bh}}(z) = N(z) M^\text{aver}_{\text{bh}} \), where \( M^\text{aver}_{\text{bh}} \) is the average black hole mass. The average black mass for faint AGNs should be larger than that for bright AGNs, as the black holes in bright AGNs are still growing through accretion (a rough estimate gives the average black hole mass in faint AGNs being about twice that in bright AGNs, if \( m^\text{aver} = 1 \) and \( t' \sim 10^8 \) yr). This leads to

\[ \rho_{\text{bh}}(z) = \frac{t'}{t'^8} \rho_{\text{bh}}(z) f_{\text{cor}}, \]

(4)

where \( f_{\text{cor}} > 1 \) is the ratio of average black hole masses of faint AGNs to bright AGNs. The black hole mass density for faint AGNs can be calculated from the HXLF by using equations (1) and (4), so that equation (3) can be rewritten as

\[ L_{X}^{\text{faint}}(E, z) = \frac{\rho_{\text{bh}}(z) f_{\text{cor}}}{10^{8} M_{\odot} t'^8} \int_{0}^{t'f} l_{X}(E, t) dt. \]

(5)

Based on the RIAF models, the X-ray light curve can be calculated, if we know how the accretion rate \( \dot{m} \) evolves with time. Unfortunately, we are still ignorant of the detailed form of \( \dot{m}(t) \). Here we introduce a timescale 1/\( t'^8 \) to describe the basic feature of the evolution of RIAFs in these faint AGNs,

\[ \int_{0}^{t'f} l_{X}(E, t) dt = l_{X}(E, 0) \frac{t'^8}{t'^8} = l_{X}^{\text{tot}}(E) \frac{t'^8}{t'^8}. \]

(6)

This timescale 1/\( t'^8 \) describes how fast the accretion rate of an RIAF declines from \( \dot{m}_{\text{tot}} \) to a rate significantly lower than \( \dot{m}_{\text{tot}} \) after the accretion mode transition. Now, equation (5) becomes

\[ L_{X}^{\text{faint}}(E, z) = \frac{\rho_{\text{bh}}(z) 1/\text{t'}^8 f_{\text{cor}}}{10^{8} M_{\odot}} = \frac{\rho_{\text{bh}}(z) t'^8}{10^{8} M_{\odot}} l_{X}^{\text{tot}}(E). \]

(7)

The contribution from the RIAFs in all faint AGNs to the cosmological XRB can be calculated as

\[ f_X(E) = \int_{0}^{t'^8} L_{X}^{\text{faint}}((1+z)E, z) dV 4\pi d_{L}^{2}(1+z) \frac{dz}{dz}, \]

\[ = \frac{1}{10^{8} M_{\odot} t'^8} \int_{0}^{t'^8} \rho_{\text{bh}}(z) l_{X}^{\text{tot}}((1+z)E) dV 4\pi d_{L}^{2}(1+z) \frac{dz}{dz}. \]

(8)

In this Letter, we conservatively adopt \( f_{\text{cor}} = 1 \).

2.2. RIAF Spectra

In order to calculate the contribution of RIAFs in faint AGNs to the XRB, we need to have the X-ray spectrum \( l_{X}^{\text{tot}}(E) \) of an RIAF around a 10\(^8\) \( M_{\odot} \) black hole accreting at the critical rate \( \dot{m}_{\text{crit}} \). We employ the approach suggested by Mannmoto (2000) to calculate the global structure of an accretion flow surrounding a Schwarzschild black hole (i.e., \( a = 0 \)) in the general relativistic frame. All the radiation processes are included in the calculations of the global accretion flow structure (see Mannmoto 2000 for details, and references therein). Unlike Mannmoto’s calculations, which are limited to cases without winds, we also calculate the cases with winds. In the spectral calculations, the gravitational redshift effect is considered, while the relativistic optics near the black hole is neglected. This will not affect our final results on the XRB, as the faint AGNs should have randomly distributed orientations and the stacked spectra would not be affected by the relativistic optics.
3. RESULTS

Three-dimensional MHD simulations suggest that the viscosity parameter $\alpha$ in the accretion flows is $\sim 0.1$ (Armitage 1998) or $\sim 0.05$–0.2 (Hawley & Balbus 2002). We assume an $\alpha$-dependent accretion rate $m = m_{out}(r/r_{out})^{\alpha}$ for the RIAFs with winds. The parameters adopted in the calculations are $\alpha = 0.2$, $m = 0.01$, the fraction of magnetic pressure $1 - \beta = 0.5$, and the fraction of dissipated energy directly heating electrons $\delta = 0.5$. An outer radius $r_{out} = 100 R_{Schw}$ is adopted in all our calculations, where $R_{Schw} = 2GM_{bh}/c^{2}$. We plot the X-ray spectra for RIAFs in Figure 1.

There is no doubt that the contribution from a normal bright AGN is important in the VHXRB, as BeppoSAX observations have shown that the power-law X-ray spectra of bright AGNs extend to several hundred keV (see, e.g., Nicastro et al. 2000). Here we consider the XRB to consist of not only the emission from type I/II bright AGNs (Compton-thin) described by this HXLF, but also the emission from RIAFs in those faint AGNs from type I/II bright AGNs (Compton-thin) described by the X-ray spectra for RIAFs in Figure 1.

With weak winds $(p_{w} = 0.2)$, we find that the hard X-ray emission alone from the RIAFs in faint AGNs has already surpassed the observed XRB, provided $t^{\text{RIAF}} = 0.05t^{\text{nu}}$. If the hard X-ray emission from both the bright type I/II AGNs and RIAFs in faint AGNs is considered, we find more strict constraints on the RIAF timescale: $t^{\text{RIAF}} < 0.01t^{\text{nu}}$ is required in most cases (this becomes $t^{\text{RIAF}} < 0.005t^{\text{nu}}$ for the RIAFs without winds).

Here we have neglected the contribution from Compton-thick AGNs. If the contribution from a Compton-thick AGN is included, the present derived RIAF accretion timescales will become even lower.

Our present calculations are based on the assumption that all AGNs described by Ueda et al.’s HXLF are bright, that is, standard bright accretion disks are responsible for their energy sources. Our RIAF spectral calculations show that $L_{X}^{\text{2-10keV}}$ is $1.48 \times 10^{41} \text{ ergs s}^{-1}$ for $p_{w} = 0$ and $5.40 \times 10^{40} \text{ ergs s}^{-1}$ for $p_{w} = 0.9$ if $M_{bh} = 10^{6} M_{\odot}$ and $m = 0.01$. As the lower luminosity limit of the HXLF extends to $10^{41.5} \text{ ergs s}^{-1}$, this means that only the faint AGNs accreting at the critical rate with black hole masses $\geq 2 \times 10^{6} M_{\odot}$ may have appeared in this HXLF. The standard disks accreting at $m > m_{out}$ around a black hole with $\approx 2 \times 10^{6} M_{\odot}$ have $L_{X}^{\text{2-10keV}} \approx 10^{42.5} \text{ ergs s}^{-1}$. This implies that some RIAF counterparts of the bright AGNs with $L_{X}^{\text{2-10keV}} \approx 10^{42.5} \text{ ergs s}^{-1}$ may be included in this HXLF. We can roughly estimate that the number ratio of these RIAF counterparts to bright AGNs with $L_{X}^{\text{2-10keV}} \approx 10^{42.5} \text{ ergs s}^{-1}$ is $\approx \tau^{\text{RIAF}}/\tau^{\text{nu}}$. Simply integrating the HXLF, we find that the ratio of the sources with $L_{X}^{\text{2-10keV}} = 10^{42.5} - 10^{44} \text{ ergs s}^{-1}$ to all AGNs described by this HXLF is about $0.13$, which implies that less than a fraction $\sim 0.13\tau^{\text{RIAF}}/\tau^{\text{nu}}$ of all sources with $L_{X}^{\text{2-10keV}} = 10^{41.5} - 10^{44} \text{ ergs s}^{-1}$ may have RIAFs. Therefore, the contribution to the XRB from those RIAF sources with $L_{X}^{\text{2-10keV}} > 10^{41.5} \text{ ergs s}^{-1}$

![Fig. 1.](image1.png) Spectra of RIAFs accreting at the critical rate $m_{out} = 0.01$ for different wind parameters $p_{w}$: 0 (black), 0.2 (green), 0.5 (red), and 0.9 (blue). A black hole mass $M_{bh} = 10^{6} M_{\odot}$, viscosity parameter $\alpha = 0.2$, fraction of the magnetic pressure $1 - \beta = 0.5$, and outer radius $r_{out} = 100 R_{Schw}$ were adopted in the calculations. The dotted lines represent the bremsstrahlung spectra of the RIAFs.

![Fig. 2.](image2.png) Contribution to the XRB from bright and faint AGNs for RIAFs with different wind strengths or without winds. The dashed lines are the observed XRB. Different-colored lines represent different values of $p_{w}$: 0.005 (green), 0.01 (red), and 0.05 (blue). The dot-dashed line represents the contribution by bright type I/II AGNs (Compton-thin), which is taken from Ueda et al. (2003). The solid lines represent the XRB contributed by bright type I/II (Compton-thin) AGNs and the RIAFs in the faint AGNs, while the dotted lines are for the contributions of RIAFs in the faint AGNs only.

4. DISCUSSION

We find that all the spectra have an energy peak at around several hundred to 1000 keV (see Fig. 1). Compared with those obtained by Di Matteo et al. (1999), our spectra have higher energy peaks. The reason is that we adopt $\delta = 0.5$, larger than theirs, which leads to higher electron temperatures in the accretion flows. From Figure 2, we find that $t^{\text{RIAF}} = 0.05t^{\text{nu}}$ is required from a comparison of our theoretical calculations with the observed XRB for any RIAF, either without winds or with strong winds. For the RIAFs without winds ($p_{w} = 0$) or with weak winds ($p_{w} = 0.2$), we find that the hard X-ray emission alone from the RIAFs in faint AGNs has already surpassed the observed XRB, provided $t^{\text{RIAF}} = 0.05t^{\text{nu}}$. If the hard X-ray emission from both the bright type I/II AGNs and RIAFs in faint AGNs is considered, we find more strict constraints on the RIAF timescale: $t^{\text{RIAF}} < 0.01t^{\text{nu}}$ is required in most cases (this becomes $t^{\text{RIAF}} < 0.005t^{\text{nu}}$ for the RIAFs without winds). Here we have neglected the contribution from Compton-thick AGNs. If the contribution from a Compton-thick AGN is included, the present derived RIAF accretion timescales will become even lower.

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may be overcalculated, but at a very low level of $\alpha_{\text{edd}}^{\text{RIAF}}/t^b$, which is negligible and will not affect our main conclusions.

We have assumed a constant lifetime $t^b$ and $t' (t^b)$ for all bright and faint AGNs, which may not be true, as suggested by Hopkins et al. (2005). However, our results on the XRB only depend on the ratio $t^b$, so our conclusions will not be altered, even if individual sources have different lifetimes, provided they have a similar time-dependent form of $\dot{m}(t)$. The XRB that results from equation (8) depends on the value of $m^\text{aver}$ as $1/m^\text{aver}$ (see eq. [1]). McLure & Dunlop (2004) estimated that the average accretion rate $m^\text{aver}$ varies from 0.1 at $z \sim 0.2$ to 0.4 at $z \sim 2$ from a large sample of SDSS quasars. If we adopt a larger $m^\text{aver} = 0.4$, the derived RIAF timescales $t^\text{RIAF}$ will be 4 times the present values. The derived timescales are proportional to the bolometric luminosity correction factor $f_{\text{cor}}$ and the uncertainty in $f_{\text{cor}}$ should not be very large, which will not affect our main conclusions. The emission in the hard X-ray bands from RIAFs is dominated by the bremsstrahlung emission and Comptonization of the bremsstrahlung photons (see Fig. 1), which are almost independent of the magnetic field strength $B$ adopted in the calculations.

Our results indicate that the accretion rate must drop to a very low rate from near-Eddington to $\sim 10^{-5}$ within a short time as compared with its bright phase (see Fig. 2 of Di Matteo et al. 2005), which is qualitatively consistent with our results. The black hole growth during the timescale $t^\text{RIAF}$ can be neglected compared with that during the bright-AGN phase, as $f^\text{RIAF} \ll t'$. However, our present calculations have not considered how the accretion rate evolves with time in detail. Advection becomes important when the RIAFs are accreting at rates $\ll m^\text{cor}$, and the black holes may swallow gases without radiating much in X-rays. So, the possibility cannot be ruled out that faint AGNs stay at accretion rates far lower than the critical value for a very long time—say, comparable to the Hubble timescale. In principle, this can also be constrained by the cosmological XRB, but this is beyond the scope of this Letter.

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