THE CORRELATION BETWEEN THE X-RAY SPECTRAL SLOPE AND THE Fe Kα LINE ENERGY IN RADIO-QUIET ACTIVE GALACTIC NUCLEI

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ABSTRACT

A significant correlation between the Fe Kα line energy and the X-ray spectral slope has been discovered among radio-quiet active galactic nuclei. The ionization stage of the bulk of the Fe Kα-emitting material is not the same in all active galactic nuclei and is related to the shape of the X-ray continua. Active galactic nuclei with a steep X-ray spectrum tend to have a fluorescence Fe Kα line from highly ionized material. In the narrow-line Seyfert 1 galaxies with a steeper X-ray spectrum (Γ < 2.1), the Fe Kα line originates from highly ionized material. In the Seyfert 1 galaxies and quasars with a flatter X-ray spectrum (Γ ≤ 2.1), the bulk of the Fe Kα emission arises from near-neutral or weakly ionized material. The correlation is an important observational characteristic related to the accretion process in radio-quiet active galactic nuclei and is driven by a fundamental physical parameter that is likely to be the accretion rate relative to the Eddington rate.

Subject headings: accretion, accretion disks — galaxies: active — X-rays: galaxies

1. INTRODUCTION

X-ray emission of active galactic nuclei (AGNs) consists of a power law with a photon index of ∼1.9 (Mushotzky 1997), a soft X-ray excess component at the lowest X-ray energies (Singh, Garmire, & Nousek 1985; Arnaud et al. 1985), a strong emission line from the K shell of iron at ∼6.4 keV (see, e.g., Tanaka et al. 1995), and the Compton-reflection hump in the energy range of ∼20–100 keV and peaking at ∼30 keV (George & Fabian 1991; Reynolds 1999). This basic form of the X-ray spectrum is easily explained in the framework of disk-corona models (e.g., Haardt & Maraschi 1993), in which an optically thin corona irradiates a dense and thin accretion disk surrounding a supermassive black hole (SMBH). The optically thick accretion disk is often assumed to be weakly ionized, radiatively efficient, and therefore cold. The broad Fe Kα line at ∼6.4 keV arises because of the fluorescence of neutral iron in the inner regions of the accretion disk (Reynolds & Fabian 1997). The Fe Kα line and the Compton reflection both arise because of the irradiation of coronal hard X-ray emission onto the disk, suggesting that any change in the Fe Kα line emission, due to some change in the accretion disk or corona, must be accompanied by a corresponding change in the reflection hump and therefore the observed shape of the X-ray continua. The energy of the Fe Kα emission depends on the ionization stage of iron and ranges from 6.4 keV for Fe I to 6.9 keV for Fe xxvi. Indeed, the rest-frame energy of the Kα emission from different AGNs has been observed to cover a range of ∼6.4–6.9 keV (see Table 1). Also, the photon index of the X-ray spectra of AGNs ranges from ∼1.7 to ∼2.5. Hence, it is of great importance to investigate whether the above two parameters are related or not.

2. THE DATA

The 2–10 keV photon indices, the rest-frame energies of Fe Kα emission, and the width of the Hβ line of 32 AGNs were obtained from the published literature and are listed in Table 1. For most of the AGNs that were observed with ASCA, the peak energy of the Fe Kα was derived by using a single Gaussian. Some AGNs, observed with XMM-Newton, showed clear evidence for the presence of both the narrow and broad components of the Fe Kα emission. For these AGNs, the line energies of narrow and broad components are listed in Table 1. All the AGNs listed in Table 1 show strong Fe Kα emission. These AGNs were selected based on the following criteria: (1) they were classified as radio-quiet and type 1 AGNs, (2) the equivalent width of the Fe Kα line (EW(Kα)) is ≥100 eV, or the line has been resolved to be broad (FWHM > 10,000 km s⁻¹), or the line is rapidly variable, and (3) the rest-frame energy of the Fe Kα line has been determined with an accuracy better than 5%. In the second criterion, it is important to exclude AGNs that show only the narrow unresolved Fe Kα line arising outside of the accretion disk. It is thought that the unresolved narrow components of the Fe Kα line with equivalent widths less than 100 eV are unlikely to arise from the inner regions of the accretion disk (Reynolds 2001). Such narrow unresolved components have been observed with Chandra and XMM-Newton from a number of AGNs (e.g., Kaspi et al. 2001; Pounds et al. 2001; Turner et al. 2002) and are found to have their peak energy at 6.4 keV with an equivalent width of ∼50–100 eV. These AGNs are not part of the sample listed in Table 1. Here the aim is to study the Fe Kα emission originating from the accretion disk.

3. THE CORRELATION

Figure 1a shows the plot of the power-law photon index against the rest-frame line energy of the Fe Kα emission for the AGNs listed in Table 1. For AGNs that show narrow as well as broad components of Fe Kα line, the line energies plotted are the rest-frame energies of the broad components that were derived by using a Gaussian or disk-line model of Fabian et al. (1989) or Laor (1991). Some AGNs show strong red wings in their Fe Kα profile that are due to relativistic effects. Such redshifted lines are not fitted by a Gaussian but are well described by the disk-line models of Fabian et al. (1989) or Laor (1991). In such cases, the appropriate rest-frame energy of the Fe Kα line is that derived from the disk-line models.

As can be seen in Figure 1a, the 2–10 keV X-ray photon index appears to be correlated with the rest-frame energy of the Fe Kα line. In order to quantify this correlation, the Spearman’s rank correlation coefficient (ρ) was calculated. For the sample of 32 AGNs, ρ is found to be 0.69 for 30 degrees of

L71
freedom. This correlation is statistically significant at a level of greater than 99.9% as inferred from the Student’s t-test.

The 2–10 keV photon index is plotted against the FWHM of the Hβ line in Figure 1b for the sample listed in Table 1. The two parameters are strongly anticorrelated ($\rho = -0.67$), with a significance level greater than 99.9%. This correlation is the same as that reported by Brandt, Mathur, & Elvis (1997) and verifies their result. In Figure 1b, AGNs with FWHM$_{H\beta} \approx 2000$ km s$^{-1}$ are the narrow-line Seyfert 1 (NLS1) galaxies (Osterbrock & Pagge 1985). Some NLS1 galaxies, e.g., NGC 4051, Mrk 359, and Mrk 478, have photon indices similar to that of broad-line Seyfert 1 (BLS1) galaxies (see Dewangan et al. 2002 for the definition).

In Figure 1c, the rest-frame energy of the Fe Kα emission is plotted against the width of the Hβ line. NLS1 galaxies show a large diversity in their Fe Kα line energies. However, the Fe Kα emission arises from near-neutral material only from those NLS1 galaxies with a flat X-ray spectrum ($\Gamma_x < 2.1$) similar to that of BLS1 galaxies. The energy of the Fe Kα emission appears to be anticorrelated with the width of the Hβ line ($\rho = -0.44$) at a significance level of 98.6%. Excluding the six NLS1 galaxies with $\Gamma_x < 2.1$, the correlation improves to a significance level of 99% ($\rho = -0.71$).

### 4. DISCUSSION

A significant correlation between the 2–10 keV photon index and the rest-frame energy of the Fe Kα line has been discovered in radio-quiet AGNs. This correlation adds to the many correlations found earlier in AGNs. Boroson & Green (1992) found numerous correlations between optical line widths and strengths. Most notable was the correlation between the width of the Hβ line and the strength of the Fe Kα emission. They identified a driving parameter "eigenvector 1" through principal component analysis. Boller, Brandt, & Fink (1996) discovered the correlation between the 0.1–2.4 keV photon index and the width of the Hβ line. Brandt et al. (1997) reported that the ASCA 2–10 keV photon index and the width of the Hβ line are also correlated. Furthermore, ROSAT and ASCA studies have confirmed that Seyfert 1 galaxies with a steeper power-law index appear to be more variable on shorter timescales (Koenig, Staubert, & Wilms 1997; Fiore et al. 1998; Turner et
al. 1999). These correlations involving X-ray and optical observations suggest that the same eigenvector 1 is responsible for the width of the Hβ line, the strength of the Fe II emission, shape of the X-ray continuum, X-ray variability, and the energy of the Fe Kα line. The eigenvector 1 is identified as the accretion rate relative to the Eddington rate ($\dot{m}/\dot{m}_{\text{Edd}}$; see, e.g., Pounds, Done, & Osborne 1995 and Brandt 2000). This implies that the extreme line energy of the Fe Kα emission of AGNs is also due to a higher fractional accretion rate $\dot{m}$.

NLS1 galaxies show a large diversity in their X-ray properties (Figs. 1b and 1c; Boller et al. 1996; Brandt et al. 1997) and can be divided into two groups: (1) NLS1 galaxies with X-ray properties similar to those of BLS1 galaxies, e.g., Mrk 359, and (2) NLS1 galaxies with extreme X-ray properties (i.e., a steeper spectrum and Fe Kα emission from highly ionized material), e.g., Ark 564. NLS1 galaxies in the former group are likely to have smaller black hole masses but similar accretion rates as that of BLS1 galaxies. The exceptionally narrow (FWHM $\sim$ 100 km s$^{-1}$) forbidden lines, FWHM$\text{Hg} \sim$ 500 km s$^{-1}$, $G_{\text{Hg}} \sim$ 1.85, and $E_{\text{Fe Kα}} \sim$ 6.4, of Mrk 359 favor such a scenario. NLS1 galaxies with extreme X-ray properties are probably the AGNs with Eddington or super-Eddington accretion rates and/or smaller black hole masses.

It is unlikely that the bulk of the Fe Kα-emitting material is moving in a preferred direction, suggesting that the Doppler effect is not responsible for the observed range of $\sim$6.4–7 keV of $E_{\text{Fe Kα}}$. For a given emissivity law and location of the Fe Kα-emitting material, the diversity in the line profile, due to gravitational effects, is limited by the range of inclination angles. For type 1 AGNs, gravitational effects may result in the observed range of energies if the Fe Kα-emitting material is highly ionized but its location with respect to the SMBH varies substantially among AGNs. In this case, the disk-line

![Graph](image_url)
fits to the Fe Kα line should always result in a rest-frame line energy of ∼6.9 keV, which is not the case (see Table 1). The energy of the Fe Kα line depends on the ionization stage of iron, and the observed range could easily be produced by neutral to H-like iron. The straightforward interpretation of the correlation between \( \Gamma_a \) and \( E_{Fe Kα} \) is that the accretion disks of AGNs with steeper X-ray continua are more ionized. Observations of H-like oxygen, nitrogen, and carbon emission lines from MCG -6-30-15 and Mrk 766 (Branduardi-Raymont et al. 2001) support the above picture. NLS1 galaxies with a steep X-ray spectrum seem to possess highly ionized accretion disks. In the disk-corona models, the 2–10 keV continuum is thought to arise from the corona, while the Fe Kα line arises as a result of fluorescence in the accretion disk. The question then is how the ionization state of the accretion disk affects the slope of the X-ray continuum.

A steeper primary X-ray continuum can be produced by Comptonization of soft photons in a cooler corona (Pounds et al. 1995). If the observed 2–10 keV continuum of AGNs is dominated by the primary emission, then the observed correlation between \( \Gamma_a \) and \( E_{Fe Kα} \) implies that cooler coronae are associated with ionized accretion disks. It is known that BLS1 and NLS1 galaxies with a steep X-ray spectrum have comparable X-ray luminosities. If the geometry of the disk-corona systems in the two types of Seyfert 1 galaxies is similar, it is unlikely that photoionization of the disk material will result in different stages of ionizations. There can be other processes, e.g., thermal ionization in the inner regions of a disk with high accretion rates. Such disks emit soft X-ray excess emission that can maintain the corona at a lower temperature (Pounds et al. 1995).

Under certain conditions, the observed 2–10 keV continuum can be dominated by the Compton-reflection component. The strength and the shape of the reflection component depends on the solid angle subtended by the accretion disk onto the corona and ionization state of the reflector. The spectral shape of the reflection component depends on the competition between the two physical processes: (1) the photoelectric absorption of the coronal photons by the atoms in the accretion disk and (2) the Compton scattering of coronal photons by the electrons in the disk. If the disk is fully ionized, then the Compton scattering dominates over the photoelectric absorption. Under these conditions, hard as well as soft X-ray photons are scattered, and the reflection hump is expected to extend to the soft X-ray regime. If the accretion rate is high, it is likely that the disk is dominated by radiation pressure (Fabian et al. 2002). Under these conditions, the disk can be clumpy, irregular, or ribbed (see Lightman & Eardley 1974 and Guilbert & Rees 1988). If the corona lies close to the disk, the solid angle subtended by the disk onto the corona can be much larger than \( 2\pi \), and coronal photons can be reflected many times before they escape. The net effect is that the resulting spectrum is dominated by reflection and is considerably steep (Ross, Fabian, & Ballantyne 2002). Thus, a highly ionized irregular disk could give rise to both the steep X-ray spectrum and the \( K\alpha \) emission from highly ionized iron. Both of these conditions are most likely to occur when the accretion rate is high and close to the Eddington rate.

5. CONCLUSIONS

A correlation between the photon index of the 2–10 keV X-ray continuum and the central energy of the Fe Kα emission has been discovered for the radio-quiet AGNs. This correlation suggests that AGNs with steep soft X-ray continua have highly ionized accretion disks.

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