THE BROAD Fe K-LINE PROFILE IN NGC 4151

JUN-XIAN WANG,1,2 YOU-YUAN ZHOU,1,2,3 AND TING-GUI WANG1,2

Received 1999 May 10; accepted 1999 July 26; published 1999 August 30

ABSTRACT

We present an analysis of the Fe K-line profile of NGC 4151 by using long ASCA observation data obtained in 1995 May. The unprecedented good data quality, which is much better in the energy band around 6.4 keV than that of the famous 4.2 day ASCA observation of MCG −6-30-15 in 1994 July, offers a unique opportunity to study the details of Fe K-line profile. Apart from those characteristics already noticed in earlier ASCA observations on this object (Yaqoob et al.; a broad and skewed profile with a strong peak at about 6.4 keV and a large red wing extending to ∼4−5 keV), which is remarkably similar to that of MCG −6-30-15, we also find a weak blue wing extending to about 8 keV, thanks to the good quality of the data. When fitted by a relativistic accretion disk line plus a narrow core at 6.4 keV, the data constrain the accretion disk to be nearly face-on, contrary to the edge-on geometry inferred from optical and UV observations. However, the extended blue wing can not be well fitted even after we include corresponding Fe Kα components. Ni Kα-line emission by an amount of 12% of Fe Kα is statistically required. An alternative explanation is a model consisting of a narrow core and two disk lines with inclinations of 58° and 0°, respectively. We suppose that the component with inclination of 58° was observed directly, consistent with its edge-on geometry, and the component with inclination of 0° was scattered into our line of sight by a Compton mirror, which might be the cool accretion disk corona proposed by Poutanen et al.

Subject headings: black hole physics — galaxies: active — galaxies: individual (NGC 4151) — line: profiles — X-rays: galaxies

1. INTRODUCTION

The fluorescent iron Kα line revealed by a 4.2 day ASCA observation in the Seyfert 1 galaxy MCG −6-30-15 has distinct features that are unique characteristics of the emission line from a relativistic disk (Tanaka et al. 1995). The line is peaked at around 6.4 keV, with a broad red wing extending down to 4 keV. The skewness of the profile toward red and the sharp blue edge near the rest-frame energy are a consequence of the combination of the relativistic Doppler effect and strong gravitational redshift and are unique to a low-inclination relativistic accretion disk; other mechanisms of the line formation produce these features less successfully (Fabian et al. 1995). However, the alternative models such as thermal Comptonization (Misra & Kembhavi 1998) cannot be ruled out completely. Both the disk-line fit (Tanaka et al. 1995) and the frequency extrema analysis (Bromley, Miller, & Pariev 1998) suggested that the inner edge of line formation region is within a few Schwarzschild radii, providing the strongest evidence ever for a supermassive black hole in this object. Similar broad-line profiles with lower statistics have also been seen in other active galactic nuclei (AGNs; Mushotzky et al. 1995; Tanaka et al. 1995; Yaqoob et al. 1995; Nandra et al. 1997; Turner et al. 1998; and references therein).

The line profile is strongly dependent on the inclination of the relativistic accretion disk (Fabian et al. 1989), thus providing a method to estimate the inclination of the inner accretion disk from line profile fitting. The inclinations from this method for a sample of Seyfert 1 galaxies are strongly constrained to be nearly face-on (Nandra et al. 1997), consistent with the expectation of the unification model of the two types of Seyfert galaxies (see Antonucci 1993 for a review). However, there are complications to this simple picture. Turner et al. (1998) found that type 2 Seyfert galaxies also possess similar iron Kα-line profiles, indicative of face-on accretion disk as well. This might be due to the strong contribution of a narrow component in these objects (Weaver & Reynolds 1998) or due to complex absorption (Wang et al. 1999b). Moreover, the rapid variability of the line equivalent width (EW) and profile observed in MCG −6-30-15 (Iwasawa et al. 1996) and NGC 4051 (Wang et al. 1999a) cannot be readily explained by any current simple accretion disk line model.

NGC 4151 is a bright nearby (z = 0.0033) Seyfert 1.5 galaxy. The edge-on orientation of its nucleus is strongly supported by the biconical geometry of the [O III] λλ5007 region (Evans et al. 1993; Pedlar et al. 1993), and the best estimated inclination is 65°. Yaqoob et al. (1995) presented the first measurement of its broad Fe K-line profile from the ASCA observations performed in 1993 May, November, and December. The apparent line profile is asymmetric, consisting of a peak at ~6.3−6.4 keV and a broad red wing extending to ~4−5 keV. When a disk-line model is fitted, the inclination angle of the disk (θ = 0°−10°) is strongly constrained to be face-on, in contrast to the edge-on geometry of this source. This problem can be eased, but not solved, by assuming an additional narrow-line contribution, presumably from the torus, to the Fe K line (θ = 25°−30°; see Yaqoob & Weaver 1997).

A much longer ASCA observation (3 days) of NGC 4151, which provides data with better statistics (Leightly et al. 1997), was carried out in 1995. In this Letter, we report measurement of the complex broad iron K-line profile and its implication.

2. THE ASCA DATA

NGC 4151 was observed by ASCA from 1995 May 10 to 12 with the solid-state imaging spectrometer (SIS) in 1 CCD mode and the gas imaging spectrometer (GIS) in PH mode. The GIS data are contaminated by a nearby BL Lac object due to their worse spatial resolution. In this Letter, we will con-
centrate on the SIS data, since they also offer much better energy resolution (Inoue 1993), which is crucial to the Fe K-line profile analysis. The data were reduced with the ASCA standard software XSELECT and cleaned using the following screening criteria: satellite not passing through the South Atlantic Anomaly, geomagnetic cutoff rigidity greater than 6 GeV cm$^{-2} \cdot$s$^{-1}$, and minimum elevation angle above Earth’s limb of 10° and 20° for nighttime and daytime observations, respectively. Source counts were extracted from a circular area of radius 3.4 for the SIS0 and SIS1, and the background counts were estimated from the blank-sky data. Spectra extracted from SIS0 and SIS1 were combined and grouped to have more than 20 counts in each bin to allow the use of $\chi^2$ statistics. Spectral analysis was carried out using XSPEC.

The ASCA observation lasted for about 3 days, and the SIS0 detector received a net exposure time of 93,000 s and an average count rate of 1.49 counts s$^{-1}$ in the 0.4–10.0 keV band, while these two parameters for the well-known 4.2 day ASCA observation on MCG $-6-30-15$ in 1994 July are 150,000 s and 1.82 counts s$^{-1}$, respectively. Although shorter exposure time and lower count rate will probably lead to worse statistics, we noticed that, because of its much harder spectrum (due to strong absorption), the actual total counts (32,000) for NGC 4151 in the 5.0–7.0 keV band are almost 3 times of those (11,000) for MCG $-6-30-15$ in the same energy band. Thus, the NGC 4151 Fe K spectrum used in this Letter has better statistics than the average MCG $-6-30-15$ spectrum and a best-ever quality Fe K-line profile.

3. SPECTRAL FITS

Following Weaver et al. (1994), we fit the underlying continuum in the 1.0–4.0 and 8.0–10.0 keV bands (to exclude the possible broad iron line region) with a model which consists of a dual absorbed power law with some fraction (a best-fit value for this Letter is ~5%) of the direct continuum scattered into our line of sight and absorbed only by the Galactic column of $2 \times 10^{20}$ cm$^{-2}$. We do not include a Compton reflection component in the spectral fits because a clear reflection component has never been detected (Mainsack & Yaqoob 1991; Yaqoob et al. 1993). Zdziarski, Johnson, & Magdziarz (1996) claimed that they detected a reflection component. However, considering the poor statistical significance of their detection (they used only a $\delta \chi^2$ of 2.7 for the their errors, yet the model was complicated), the complex intrinsic continuum which was unknown, and the cross calibration of two different satellites (Ginga and GROIOSSE) which is not perfect, we think that their result is questionable.

Our model can describe the data reasonably well ($\chi^2 = 364$ for 325 degrees of freedom [dof]), and the best-fit model parameters converge to $F = 1.30 \pm 0.07$, $N_{\text{h}}(\text{low}) = 3.2 \times 10^{22}$ cm$^{-2}$ (covering ~40% of the source), and $N_{\text{h}}(\text{high}) = 15.9 \times 10^{22}$ cm$^{-2}$ (covering ~60% of the source). The index is slightly flatter than that seen previously for NGC 4151 as derived from data weighted toward higher energies (Yaqoob et al. 1993). We have also tried a model consisting of a power law absorbed by ionized material (Zdziarski et al. 1995) plus a fraction of scattered underlying continuum, but we failed to get a satisfactory fit ($F = 1.00$, $\chi^2 = 393$ for 326 dof).

The profile of the iron K line, which is similar to and much better defined than the one presented by Yaqoob et al. (1995), is shown in Figure 1a. The line shows a strong narrow peak around 6.4 keV and a huge red wing, containing a second slightly weak peak at around 5.2 keV, extending to ~4.5 keV. In this respect, the line profile of NGC 4151 is remarkably similar to that seen in MCG $-6-30-15$ (see Fig. 1b for comparison). We also find that a weak blue wing extending to about 8 keV, which is just visible in Figure 2c of Yaqoob et al. (1995), is now clearly seen, thanks to the greatly improved statistics. The brightness of this source rules out the possibility that the blue wing is caused by improper background subtraction (only 1% of the count rate at 7.0–8.0 keV is due to the background).

First, we fit the line with a disk-line model (Fabian et al. 1989) plus a narrow core at 6.4 keV which is presumably from the torus and also statistically required ($\Delta \chi^2 = -46$). Although expected in theory, the fluorescent Fe Kβ line is always ignored when fitted to data with much lower quality. Considering the high quality of the data in this Letter, we also include the corresponding Fe Kβ components (disk-line plus narrow core) in all of our models by amounts of 11.3% of Fe Kα (George & Fabian 1991). In fact, Fe Kβ components are also statistically required here ($\Delta \chi^2 = -36$). The outer radius ($R_o$) of the disk is fixed at 1000 $R_g$ ($R_g = GM/c^2$) to minimize the numbers of free parameters because the fits are not sensitive to the value for the outer radius. The best-fit value is also consistent with
1000 $R_g$ when it is allowed to vary. Considering the strong peak at 6.4 keV, we fixed the disk-line energy at 6.4 keV in the source rest frame. Results of this fit are given in Table 1 (model A). The inclination of the disk is $27^\circ$, similar to the value obtained by Yaqoob & Weaver (1997). However, the blue wing of the line beyond 6.8 keV has not been well fitted (see Fig. 2a).

In the accretion disk model context, the high-energy blue wing can be produced by an accretion disk with high inclination angle. The blue wing, as well as the edge-on geometry of NGC 4151 inferred from optical and UV observations (Evans et al. 1993), motivated us to add an extra component of a disk line with large inclination to model A (model B; Fe K$\beta$ components also included). We assume that the inner and outer radii of the disk for these two disk-line components are the same, while the emissivity index $q (F_{\text{line}} \propto R^{-q})$ is allowed to vary independently considering the fact that line photons from different parts of the disk may have different scattering fractions. The results are also given in Table 1. The model can fit the observed line profile fairly well (see Fig. 2b). The improvement of model B to model A is significant ($\Delta \chi^2 = -19$). As expected, the second disk component requires a high inclination of $58^\circ-12^\circ$ degrees, while the first component requires a face-on disk ($0^\circ-32^\circ$ degrees).

Alternatively, the high-energy blue wing between 6.8 and 8.0 keV may also be produced by the Ni K$\alpha$-line emission at 7.48 keV. In order to reduce the excesses in the residuals between 6.8 and 8.0 keV in Figure 2a, corresponding Ni K$\alpha$ components by amounts of $12^\circ-6^\circ$ of Fe K$\alpha$ have to be added to model A (see Fig. 2c, $\Delta \chi^2 = -13$).

4. DISCUSSION

Zdziarski et al. (1996) argued that the ASCA data of NGC 4151 obtained in 1993 May can be modeled by complex absorption and a narrow Fe K line only, with no broad line required, contrary to the results of Yaqoob et al. (1995) and this Letter. However, the ASCA data used by Zdziarski et al. have much lower signal-to-noise ratios. Through fitting the unprecedented high-quality spectra of NGC 4151 obtained by ASCA in 1995, we find a prominent broad Fe K-line profile in NGC 4151 (see Fig. 1), which is remarkably similar to that of MCG $-6-30-15$. A model consisting of a dual absorbed power law plus a scattered component and a narrow Fe K line at 6.4 keV ($\sigma = 0.11^{+0.06}_{-0.05}$) fits the data (1.0–10.0 keV) poorly ($\chi^2 = 706$ for 598 dof) and results in broad systematic positive residuals around 6.0 keV (see Fig. 2d). An extra broad line is statistically required ($\Delta \chi^2 = -78$).

The high signal-to-noise profile of NGC 4151 obtained in this Letter shows a strong narrow peak around 6.4 keV and a huge red wing, containing a second slightly weak peak at around 5.2 keV, extending to $\sim 4.5$ keV. In this respect, the line profile of NGC 4151 is remarkably similar to that seen in MCG $-6-30-15$. We also find that a weak blue wing extending to about 8.0 keV, which is just visible in Figure 2c of Yaqoob et al. (1995), is now clearly seen (Fig. 1a), thanks to the greatly improved statistics. There may also be such a weak blue wing in the Fe K profile of MCG $-6-30-15$ (see Fig. 1b).

When fitted by the disk-line model plus a narrow core, a face-on disk is also required ($\theta = 27^\circ$), contrary to the edge-on geometry inferred from optical and UV observations (Evans et al. 1993; Pedlar et al. 1993). We consider that the Compton mirror of Poutanen et al. (1996), who proposed that the central source of NGC 4151 is completely hidden from our line of sight and observed X-ray radiation is produced by scattering in the higher, cooler parts of the accretion disk corona, or in a wind, could solve the problem well. We also want to point out that scattering by an “ionizing cone” would also explain the similarity of Fe K-line profiles seen in Seyfert 2 galaxies and in Seyfert 1 galaxies (Turner et al. 1998), indicating reprocessing by face-on disks and contradicting the expectation of the unification scheme. The variability properties of the Fe K line are important to test such scattering hypothesis.

Besides the broad profile of the Fe K line, the blue wing extending to about 8.0 keV (see Fig. 1a), which could not be well fitted by a simple disk line plus a narrow core even after the corresponding Fe K$\beta$ components are included, should also be paid much attention to. One possible explanation is that we observe not only a broad Fe K line in NGC 4151, but also a corresponding Ni K$\alpha$ line by an amount of $12-5\%$ of Fe K$\alpha$. This may be the first detection of Ni K$\alpha$ fluorescent line emission in the X-ray spectrum of AGNs.

However, we notice that the energy of Ni K$\alpha$ line is just above that of the Fe K absorption edge. The line flux, which is sensitive to the Ni abundance and X-ray spectral slope, can

### Table 1

Fe K-Line Fits

| Model | $\chi^2$/dof | $R_g (R_o)$ | $\text{EW}_{\text{core}}$ (eV) | $\text{EW}_{\text{disk}}$ (eV) | $q$ | $\theta$ |
|-------|-------------|-------------|-------------------------------|-------------------------------|-----|--------|
| A ... | 628/599     | 8.9$^{+0.2}_{-0.1}$ | 71$^{+13}_{-12}$           | 276$^{+21}_{-24}$           | $-4.3^{+0.7}_{-0.6}$ | 27$^{+1}_{-1}$ |
| B ... | 609/596     | 6.0$^{+0.2}_{-0.1}$ | 89$^{+11}_{-10}$           | 136$^{+23}_{-27}$           | $-2.0^{+0.4}_{-0.3}$ | 58$^{+12}_{-12}$ |
|       |             |             |                               |                               | $-3.5^{+0.2}_{-0.3}$ | $0^{+5}_{-2}$ |

Note.—Errors are given at the 90% level. The energy of the narrow core is fixed at 6.4 keV in the galaxy rest frame and the line width fixed at zero. Model A: a single cold disk line (6.4 keV in the galaxy rest frame) plus a narrow core; model B: two cold disk lines with different inclinations plus a narrow core. Fe K$\beta$ components by amounts of 11.3% of Fe K$\alpha$ are included in both models.
be substantially reduced due to photoelectron absorption by Fe atoms. So, the contribution of Ni Kα emission line might be much weaker than expected. An alternative explanation to the weak blue wing is an extra Fe K disk line with high inclination angle (it is also possible that both the Ni Kα components and the extra disk line are important in reality). Poutanen et al. (1996) assumed that the central source is completely hidden from our line of sight by the thick part of the accretion disk wind or by the broad emission-line clouds. However, it is plausible to suppose that the thick material covers the X-ray only partially, and part of the central continuum is seen directly. The fast variability and the complex absorption of the X-ray continuum seem to support this idea. The results of the two-disk component model fit (model B) are fully consistent with this picture. Poutanen et al. (1996) assumed that the scattering region is situated along the axis of the accretion disk in the form of a cone. The half-opening angle of the “ionized cone” determined from the optical and UV observation is about 35° (see Fig. 10 of Evans et al. 1993), and the angle-averaged line profile in the scattered light should resemble the one from a face-on disk, which corresponds to the low inclination line component in our two disk-line fit. The direct component should show the same inclination as the system, which is 65° inferred from optical and UV observations. We got an inclination of 58.13° degrees for this line component, which is in good agreement with interpreting it as a direct component. The comparable EWs of the two line components suggests that the flux of the X-ray scattered should be commensurate roughly with the directly observed flux. The slightly lower parameter $q$ of the direct disk-line indicates that more direct Fe K photons can be observed from large disk radii.

This work is supported by the Chinese National Natural Science Foundation, the PanDeng Project, and the Foundation of Ministry of Education. We thank the referee for many critical comments, especially on the possibility of Ni Kα contribution, which significantly improved the presentation of this Letter.

REFERENCES

Antonucci, R. 1993, ARA&A, 31, 473
Bromley, B. C., Miller, W. A., & Pariev, V. I. 1998, Nature, 391, 54
Evans, I. N., Tsvetanov, Z., Kriss, G. A., Ford, H. C., Ciganoff, S., & Koratkar, A. P. 1993, ApJ, 417, 82
Fabian, A. C., Nandra, K., Reynolds, C. S., Brandt, W. N., Otani, C., Tanaka, Y., Inoue, H., & Iwasawa, K. 1995, MNRAS, 277, L11
Fabian, A. C., Rees, M. J., Stella, L., & White, N. E. 1989, MNRAS, 238, 729
George, I. M., & Fabian, A. C. 1991, MNRAS, 249, 352
Inoue, H. 1993, Exp. Astron., 4, 1
Iwasawa, K., et al. 1996, MNRAS, 282, 1038
Leighly, K. M., et al. 1997, X-Ray Imaging and Spectroscopy of Cosmic Hot Plasmas, ed. F. Makino & K. Mitsuda (Tokyo: Universal Academy Press), 291
Maisack, M., & Yaqoob, T. 1991, A&A, 249, 25
Misra, R., & Kemhavì, A. K. 1998, ApJ, 499, 205
 Mushotzky, R. F., et al. 1995, MNRAS, 272, L9
Nandra, K., George, I. M., Mushotzky, R. F., Turner, T. J., & Yaqoob, T. 1997, ApJ, 477, 602
Pedlar, A., et al. 1993, MNRAS, 263, 471
Poutanen, J., Sikora, M., Begelman, M. C., & Magdziarz, P. 1996, ApJ, 465, L107
Tanaka, Y., et al. 1995, Nature, 375, 659
Turner, T. J., George, I. M., Nandra, K., & Mushotzky, R. F. 1998, ApJ, 493, 91
Wang, J. X., Zhou, Y. Y., Xu, H. G., & Wang, T. G. 1999a, ApJ, 516, L65
Wang, T. G., Mihara, T., Otani, C., Matsuoka, M., & Awaki, H. 1999b, ApJ, 515, 567
Weaver, K. A., & Reynolds, C. S. 1998, ApJ, 503, L39
Weaver, K. A., Yaqoob, T., Holt, S. S., Mushotzky, R. F., Matsuoka, M., & Yamauchi, M. 1994, ApJ, 436, L27
Yaqoob, T., Edelson, R., Weaver, K. A., Warwick, R. S., Mushotzky, R. F., Serlemitsos, P. J., & Holt, S. S. 1995, ApJ, 453, L81
Yaqoob, T., Warwick, R. S., Makino, F., Otani, C., Sokoloski, J. L., Bond, I. A., & Yamauchi, M. 1993, MNRAS, 262, 435
Yaqoob, T., & Weaver, K. A. 1997, X-Ray Imaging and Spectroscopy of Cosmic Hot Plasmas, ed. F. Makino & K. Mitsuda (Tokyo: Universal Academy Press), 201
Zdziarski, A., Ghisellini, G., George, I. M., Fabian, A. C., Svensson, R., & Done, C. 1995, ApJ, 363, L1
Zdziarski, A. A., Johnson, W. N., & Magdziarz, P. 1996, MNRAS, 283, 193