Iron K line Variability in the Low-Luminosity AGN NGC 4579

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ABSTRACT

We present results of new ASCA observations of the low-luminosity AGN (LLAGN) NGC 4579 obtained on 1998 December 18 and 28, and we report on detection of variability of an iron K emission line. The X-ray luminosities in the 2–10 keV band for the two observations are nearly identical ($L_X \approx 2 \times 10^{41}$ ergs s$^{-1}$), but they are $\sim$35% larger than that measured in 1995 July by Terashima et al. An Fe K emission line is detected at 6.39 $\pm$ 0.09 keV (source rest frame) which is lower than the line energy 6.73 $^{+0.13}_{-0.12}$ keV in the 1995 observation. If we fit the Fe lines with a blend of two Gaussians centered at 6.39 keV and 6.73 keV, the intensity of the 6.7 keV line decreases, while the intensity of the 6.4 keV line increases, within an interval of 3.5 yr. This variability rules out thermal plasmas in the host galaxy as the origin of the ionized Fe line in this LLAGN. The detection and variability of the 6.4 keV line indicates that cold matter subtends a large solid angle viewed from the nucleus and that it is located within $\sim$ 1 pc from the nucleus. It could be identified with an optically thick standard accretion disk. If this is the case, a standard accretion disk is present at the Eddington ratio of $L_{\text{Bol}}/L_{\text{Eddington}} \sim 2 \times 10^{-3}$. A broad disk-line profile is not clearly seen and the structure of the innermost part of accretion disk remains unclear.

Subject headings: galaxies: active — galaxies: individual(NGC 4579) — galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

1. Introduction

Fe line emission in AGNs is an X-ray spectral feature produced through reprocessing by the matter surrounding the nucleus, and it can be used as a probe of the matter in the vicinity of the

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central black hole, such as accretion disks. Broad Fe emission lines have been detected in a number of Seyfert 1 galaxies, and they have been interpreted as arising from a relativistic accretion disk (e.g. Tanaka et al. 1995; Nandra et al. 1997). Fe K emission has also been detected in several low-luminosity AGNs (LLAGNs). The origin of Fe lines in these objects, however, is unclear. The line centroid energy of some LLAGNs is close to 6.7 keV (Ishisaki et al. 1996; Serlemitsos et al. 1996; Iyomoto et al. 1997; Terashima et al. 1998a, hereafter T98; Roberts, Warwick, & Ohashi 1999), which is higher than 6.4 keV as seen in Seyfert 1s, while some objects show a line at 6.4 keV (Terashima, Kunieda, & Misaki 1999). Possible origins of the Fe line at 6.7 keV include an ionized standard accretion disk, a thermal plasma in the outer region of an advection-dominated accretion flow (Narayan, & Raymond 1999), an ionized absorber and emitter along the line-of-sight (Pellegrini et al. 2000), or a thermal plasma in the host galaxy (Ptak et al. 2000). If the higher line energy is due to ionized iron, the problem arises as to how to achieve a high degree of ionization given the low luminosities and low accretion rates in LLAGNs. The variability of Fe lines provides information on the location of the line-emitting region, and thus constraints on the origin of the lines. Studies of Fe lines in LLAGNs are also of great importance to understand the structure of accretion disks in low luminosity objects.

NGC 4579 contains an LLAGN with \( L_X(2–10 \text{ keV}) = 1.5 \times 10^{41} \text{ ergs s}^{-1} \) (we assume a distance of 16.8 Mpc; Tully 1988). An ASCA observation was made on 1995 June 25, and an Fe K line is detected at \( 6.73^{+0.13}_{-0.12} \text{ keV} \) (source rest frame) with an equivalent width (EW) of \( 490^{+180}_{-190} \text{ eV} \) and a width of \( 0.17^{+0.11}_{-0.12} \text{ keV} \) (T98). We observed NGC 4579 again with ASCA in 1998 to search for possible variability of the Fe line. In this Letter, we report the change of the line centroid energy associated with a continuum luminosity increase of about 35%.

2. The ASCA Data

We observed NGC 4579 on 1998 Dec. 18 and 28 with the ASCA satellite (Tanaka, Inoue, & Holt 1994). The two Solid-State Imaging Spectrometers (SIS0 and SIS1; Burke et al. 1994) were operated in the ICCD Faint mode. The two Gas Imaging Spectrometers (GIS2 and GIS3; Ohashi et al. 1996; Makishima et al. 1996) were operated in the nominal pulse height mode.

X-ray spectra were accumulated from circular regions with radii of 4′ for the SIS and 6′ for the GIS. Background spectra were taken from a source-free region in the same field. The effective exposure times, after data screening, were 18.6 ks for each SIS and 19.6 ks for each GIS on December 18, and 17.6 ks for each SIS and 19.6 ks for each GIS on December 28. The count rates were similar for both observations: 0.14 counts s\(^{-1}\) for SIS and 0.13 counts s\(^{-1}\) for GIS, after background subtraction. The spectra from SIS0 and SIS1 were combined, as were those from GIS2 and GIS3. We fitted the SIS0 plus SIS1 spectra and the GIS2 plus GIS3 spectra simultaneously. It is known that SIS and GIS spectra at the low-energy band (<1 keV) are inconsistent with each other due to accumulated radiation damage of the SIS (see Yaqoob et al. 2000). In order to minimize the uncertainty in the low-energy band, we used the region 1.0–10 keV for the SIS. We confirmed that
the SIS and GIS data within this band yield statistically consistent spectral fits.

3. Results

We fitted the combined spectrum of the two observations in 1998. At first we fitted the spectrum with a power law plus Gaussian model and a thermal bremsstrahlung plus Gaussian model. The former model provided an acceptable fit with $\chi^2 = 201.0$ for 227 degrees of freedom (dof). The latter model resulted in a significantly worse fit with $\chi^2 = 302.7$ for 227 dof. Spectral features of a soft thermal plasma, detected in the 1995 observation, were not clearly seen in the residuals. We tried to add a Raymond-Smith thermal plasma component (hereinafter RS) to the power law plus Gaussian model. The temperature and abundance of the RS component were fixed at the values of T98 ($kT = 0.90$ keV and abundance = 0.5 solar), and the normalization was left to vary. The absorption column density for the RS component was fixed at the Galactic value ($N_H = 3.1 \times 10^{20}$ cm$^{-2}$; Murphy et al. 1996). The $\chi^2$ improved only by $\Delta \chi^2 = 1.0$. Thus we found no clear evidence for the presence of soft thermal emission in the 1998 observation. This is probably for the following reasons. First, the flux of the hard component has brightened by a factor of 1.35 from 1995, and thus the soft thermal component has been diluted. Second, we ignored the soft energy band below 1 keV of the SIS data in the fit, where the soft component is expected to be more prominent. The spectral slope of the hard component is nearly unaffected by the addition of the soft thermal component, while the absorption column density depends on it. We use the power law + Gaussian + RS model in the following analysis.

The best-fit parameters for the continuum and X-ray fluxes in the 2–10 keV band are shown in Table 1, as well as the fitting results of the 1995 data taken from T98. The Fe line parameters are summarized in Table 2. The SIS and GIS spectra (along with the best-fit continuum model), and ratios of data to the best-fit continuum around Fe lines in the 1998 observation are shown in Figure 1. Ratios of data to the best-fit continuum for the 1995 observation are also shown in Figure 1 for comparison. The hard X-ray luminosity in the 2–10 keV band ($L_X = 2.0 \times 10^{41}$ ergs s$^{-1}$) is $\sim 35\%$ larger in 1998 than in 1995. Although the best-fit spectral slope has slightly steepened, the statistical errors overlap each other. No significant change of the absorption column density is seen either, although the errors are large because of the limited energy band of SIS used in the analysis. An intriguing spectral change is the centroid energy of the the Fe line. The line center energy varied from $6.73^{+0.13}_{-0.12}$ keV in 1995 to $6.39 \pm 0.09$ keV in 1998. Confidence contours for the line center energy versus normalization for the two observations are shown in Figure 2. The change of the line center energy is significant at more than 90% confidence level for two interesting parameters. Note that the calibration uncertainty of the energy scale is less than 1%. We examined the gain uncertainties by using the gold edge around 2.3 keV and the Cu-K line of the GIS detector background and found no evidence for a significant gain shift larger than the 1% level. We also confirmed that all the four detectors provided Fe K line center energies consistent with each other within 1% using a recent observation of the bright AGN NGC 5548 in 1998 June and July.
The change of the line center energy could be caused by a change of the ionization state of the line emitter or by variability of multiple emission lines with different line centroid energies. In order to quantify the second possibility, we modeled the line feature with a combination of two Gaussians. We fixed the line center energies and widths of each line at the best-fit values in 1995 and 1998. The obtained EWs and intensities are shown in Table 2 and Figure 3. The intensity and EW of the 6.7 keV line decreased significantly. The intensity of the 6.4 keV line significantly increased, while the EW marginally increased. The continuum parameters in this fit are same as in the single Gaussian model fits shown in Table 1. If we assume zero width for the 6.7 keV line instead of the best-fit value in 1995, the conclusion on line variability is unchanged.

Finally, we fitted the spectra of the two observations in 1998 separately to search for spectral variability on a time scale of 10 days. We used the same model in the fit of the combined spectrum. The Fe line was modeled with a single Gaussian. The obtained spectral parameters are also summarized in Table 1 and Table 2. The X-ray luminosity in the 2–10 keV band is slightly (∼15%) higher in the first observation compared to the second. We found no clear spectral change between these two observations.

4. Discussion

We found that the center energy of the Fe K line in NGC 4579 decreased in 3.5 yrs, while the luminosity in the 2–10 keV band increased by 35%. We examined two models to represent the observed variability: a single Gaussian model and a double Gaussian model. In the double Gaussian model, the center energies were fixed at 6.39 keV and 6.73 keV. The results of these model fits indicate that the line intensity of the 6.7 keV line varied within an interval of 3.5 yr. This variability indicates that the emitter of the Fe line at 6.7 keV is located within ∼1 pc from the nucleus, and thus rules out hot gas in the host galaxy (starburst activity and/or ridge emission, which is diffuse X-ray emission with $kT \sim 5 – 10$ keV, as observed in our Galaxy) as the origin of the 6.7 keV Fe line. On the other hand, the Fe line at 6.4 keV has an origin in fluorescence in cold or slightly ionized matter illuminated by a central X-ray source (Makishima 1986). Thus, the observed Fe lines at 6.4 keV and 6.7 keV most likely originate from the AGN itself rather than from hot gas further out in the host galaxy. The relatively strong 6.4 keV line in 1998 (EW = 250$^{+105}_{-95}$ eV) indicates that cold matter subtends a large solid angle viewed from the nucleus (e.g., George & Fabian 1991). A part of the line could come from an obscuring torus which is assumed in unified models of AGNs (e.g., Antonucci 1993). If the torus is present and located at further than 1 pc from the center, the Fe line from it does not vary within an interval of ∼3 yr. Then, the torus contribution can be at most $8.5 \times 10^{-6}$ photons$^{-1}$ s$^{-1}$ cm$^{-2}$, which is the measured 90% confidence upper limit on the constant 6.4 keV line from the 1995 observation (see Table 2). This line flux corresponds to an EW of 155 eV for the continuum level in 1998. The rest of the 6.4 keV line should come from the region closer to the nucleus. Such a Fe line emitter could be identified with an optically thick accretion disk. If this is the case, a standard accretion disk should exist...
even at the low Eddington ratio of NGC 4579 \( (L_{\text{Bol}}/L_{\text{Eddington}} = 2.0 \times 10^{-3}; \text{Ho} 1999) \). The presence of an optically thick accretion disk is consistent with the estimate of the transition radius from an advection dominated accretion flow to a standard disk \( (\sim 100 \text{ Schwarzschild radii}) \) by Quataert et al. (1999). However, the suggestion of a truncated disk might not be appropriate to achieve the observed large equivalent width \( (\approx 250 \text{ eV}) \). Therefore, cold matter beyond the accretion disk, such as an obscuring torus, must contribute somewhat to the observed EW of the 6.4 keV line, if the truncated disk interpretation is correct.

The origin of the 6.7 keV line seen in 1995 still remains puzzling, however. If the Fe lines in 1995 and 1998 originated from the same region, the decrease of ionization state responding to the small flux increase of only 35% is difficult to be explained by photoionization under an assumption of a constant density. If the ionized matter is located far from the nucleus, the observed behavior of the Fe line could be due to a time lag between the continuum and Fe line variability. The X-ray flux in the 0.5–2 keV band observed with the ROSAT PSPC in 1991 Dec. is a factor of 2.3 higher than that of the first ASCA observation in 1995 June (Ptak et al. 1999). Therefore, the decrease of ionization state might be explained by a time lag effect, if the Fe line emitter is located 1 pc away from the nucleus. In order to explain the change of ionization state from Fe XXV (6.7 keV line) to Fe XVII or less (6.4 keV line), the ionization parameter \( \xi = L/nR^2 \) should change from \( \log \xi \approx 3 \) to 2 (e.g., Kallman, & McCray 1982), where \( L, n, R \) are the luminosity of ionizing photons, the number density of photoionized matter, and the distance from the ionizing source to the photoionized matter, respectively. The observed variability, however, is not enough to explain the change of the ionization parameter unless the density and/or geometry of the ionized matter also changed, or large-amplitude variability occurred during the unobserved span. Long-term variability of a factor 10 is reported in only a few objects (M81, Pellegrini et al. 2000; and possibly M51, Terashima et al. 1998b).

Alternatively, the 6.4 keV and 6.7 keV lines may originate from different regions. If most of the 6.4 keV line comes from the torus and the 6.7 keV line is from different photoionized matter, the disappearance of the 6.7 keV line might be understood by increasing the ionization state such that the gas is almost fully ionized. In this case, the 6.4 keV line could vary in response to the continuum variability with some time lag which depends on the size and geometry of the torus. However, the small flux change, again, is not enough to change the ionization state so drastically.

Thus, it is conceivable that the physical conditions (density and/or geometry) of the ionized matter changed between the two observations whether the 6.4 keV and 6.7 keV lines originate from a single region or different regions. Such a change could be caused by a change of the ionization balance in the surface layer of the standard accretion disk, or in the boundary region between the standard disk and the advection-dominated flow. It is worth noting that there are several Seyfert 1 galaxies showing the change of Fe K line centroid energy accompanied by small variations in the continuum luminosity (Weaver, Gelbord, & Yaqoob 2000). The cause of such variability, however, is yet to be understood. We note also that a drastic change of Fe line profile is observed during a flare in MCG–6–30–15 (Iwasawa et al. 1999), although the time scale they observed is much shorter
than ours. The peak energy of the Fe line during the flare was around 5 keV and such a profile change can be interpreted as being due to a flare occurring very close to the black hole (Iwasawa et al. 1999).

The observed line does not show an obvious asymmetric profile skewed toward lower energies, a signature expected from a relativistic disk (e.g., Fabian et al. 1989) and one which is observed in many Seyfert 1 nuclei (Tanaka et al. 1995; Nandra et al. 1997). The line width is evidently rather small; we place an upper limit of \( \sigma < 0.16 \) keV. Our data, unfortunately, do not have sufficient signal-to-noise ratio to confirm the presence or absence of disklike kinematic features in NGC 4579. Future measurements of the line profile using higher energy resolution and larger effective areas will be crucial to investigate the origin of the Fe line and the structure of the accretion disk in LLAGNs.

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Fig. 1.— (a) ASCA SIS (with circle) and GIS spectra of NGC 4579. The data sets from two observations in 1998 are combined. The solid histograms are the best-fit model but the normalization of the Gaussian component is set to be zero. The dotted and dashed histograms represent the Raymond-Smith and the power-law component, respectively. (b) Ratio of the data to the best-fit model around Fe lines in the 1998 observation and (c) 1995 observation. The normalization of the Gaussian component is set to be zero. The crosses with and without filled circle are SIS and GIS data, respectively. The energy scale is not redshift corrected.

Fig. 2.— Confidence contours ($\Delta \chi^2 = 2.3, 4.6,$ and $9.1$) for the line energy and normalization. Dashed lines are for the 1995 observation and solid lines are for the combined spectrum of the two 1998 observations. The fitting model is Raymond-Smith + Power-law + Gaussian. The energy scale is redshift corrected.

Fig. 3.— The equivalent width and intensity of the 6.4 keV and 6.7 keV line for the 1995 and 1998 observations. A double Gaussian model with centroid energies fixed at 6.4 keV and 6.7 keV is assumed for the Fe line.
Table 1: Results of spectral fitting to the SIS and GIS spectra of NGC 4579

Note. — The fitting model is Raymond-Smith + Power-law + Gaussian. (f) in the table denotes a frozen parameter. The absorption column for the RS component is assumed to be the Galactic value. The quoted errors are at the 90% confidence level for one interesting parameter.

Table 2: Gaussian fits to the iron K line

Note. — The line energies are at the source rest frame. (f) in the table denotes a frozen parameter. The errors are 90% confidence range for one interesting parameter.
