DETECTION OF ABSORPTION FEATURES IN THE X-RAY SPECTRUM OF THE NARROW-LINE QUASAR PG 1404+226: POSSIBLE EVIDENCE OF ACCRETION DISK WINDS

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Abstract

We present the results of an analysis of data from XMM-Newton and Chandra observations of the high-luminosity narrow-line quasar PG 1404+226. We confirm a strong soft X-ray excess in the X-ray spectrum, and we find rapid variability (a factor of 2 in about 5000 s). When the X-ray spectrum is fitted with a two-component model that includes a power-law and a blackbody component, we find that low-energy absorption lines are required to fit the data. If we interpret these lines as due to highly ionized species of heavy elements in an outflowing accretion disk wind, an outflow velocity of ∼26,000 km s⁻¹ could be derived. One interesting feature of the present observation is the possible detection of variability in the absorption features: the absorption lines are visible only when the source is bright. From the upper limits of the equivalent widths of the absorption lines during the low-flux states and also from the model-independent pulse-height ratios, we argue that the strength of absorption is lower during the low-flux states. This constrains the physical size of the absorbing medium within 100 Schwarzschild radius (R_s) of the putative supermassive black hole. We also find a marginal evidence of a correlation between the strength of the absorption line and the X-ray luminosity.

subject headings: galaxies: active — galaxies: Seyfert — quasars: individual (PG 1404+226) — X-rays: galaxies

1. INTRODUCTION

Narrow-line Seyfert 1 galaxies (NLS1s) have very remarkable X-ray properties: they show evidence of a strong excess of soft X-rays (dominant below ∼2 keV) above the hard X-ray continuum extrapolation and rapid X-ray variability (Boller et al. 1996). Complex absorption features are also common in many of these sources. Recently, Pounds et al. (2003a, 2003b) detected several absorption lines in the narrow emission line quasars PG 1211+143 and PG 0844+349, which are blue-shifted indicating relativistic outflow of highly ionized material. They suggest that these outflows form a significant component in the mass and energy budgets of systems accreting at or above the Eddington rate (King & Pounds 2003).

PG 1404+226 (V = 15, M = −23.4, z = 0.098) is one of the most extreme narrow-line Fe ii quasars. Its Hβ FWHM is 880 km s⁻¹ (Boroson & Green 1992). The ROSAT spectrum (0.1–2 keV) of PG 1404+226 is steep (Γ ∼ 3) and shows rapid (factor of 2 in 10 hr) flux variability. Moreover, flux-selected spectral analysis revealed the presence of an absorption edge around 0.8–1 keV whose energy shifts to higher value when the source brightens (Ulrich & Molendi 1996). The X-ray spectrum of PG 1404+226 was variable during an ASCA observation (Comastri et al. 1997; Ulrich et al. 1999, hereafter U99) and characterized by a strong soft excess below 2 keV whose luminosity in the 0.4–2 keV band (7 × 10⁴³ ergs s⁻¹) was a factor of 3 greater than 2–10 keV luminosity. Comastri et al. (1997) have also found an absorption edge at 1.07 keV, and they suggested an overabundance of iron. Leighly et al. (1997) compared the absorption feature found in the ASCA spectrum with absorption by ionized oxygen and derived a high velocity of ionized outflow from that object.

In this Letter we present the XMM-Newton and Chandra observations of PG 1404+226. We detect absorption features in the XMM-Newton data and find some evidence for such lines in the Chandra data. We have reanalyzed ASCA data, which corroborate this conclusion. The source shows high variability in all three observations, and most remarkably, the line features show variability in timescales of ∼5000 s, giving a direct dynamical size constraint of 100R_s for the absorbing medium.

2. DATA AND ANALYSIS

PG 1404+226 was observed by XMM-Newton on 2001 June 18 using the European Photon Imaging Camera (EPIC) and the reflection grating spectrometer (RGS) for about 21 ks. RGS data are not useful because of poor signal-to-noise ratio. The observation data files were processed and filtered using the same criterion as discussed in Dasgupta et al. (2004). The high-energy particle background flaring intervals were excluded. This resulted in a “good” exposure time of ∼14 ks for the EPIC-PN. The net count rate is 0.66 s⁻¹. The Chandra High Energy Transmission Grating Spectrometer observation of this source was performed during 2000 July 22 for a total duration of 80 ks. The spectrum is created using the 0th order image of the source because of low counts collected in high-energy and mid-energy grating. PG 1404+226 was observed by the ASCA Gas Imaging Spectrometer/ Solid-State Imaging Spectrometer (GIS/SIS) on 1994 July 13–14. In this Letter SIS data are reanalyzed. The SIS was operating in 1 CCD mode, and the data were collected in Faint mode. Standard criterion for good time selections (U99) have been applied. EPIC-PN light curves of bin size 500 s (background-subtracted) of PG 1404+226 in the energy range 0.3–1 keV (soft), 1–10 keV (hard) are plotted in Figure 1. The energy bands were chosen to separate approximately the two spectral components—a power-law and a soft excess component generally observed from NLS1s (Leighly 1999). It is evident that the X-ray emission from PG 1404+226 varied strongly during the XMM-Newton observation. The average count rates in the low- and high-flux states (demarcated by dotted lines in Fig. 1) are 0.26 ± 0.01 and 0.69 ± 0.02 s⁻¹, respectively, in the soft band and 0.029 ±
0.007 and 0.042 ± 0.007 s⁻¹, respectively, in the hard. The hardness ratio (defined as the ratio of the flux of the hard band to that of the soft band) is decreasing with time, implying that the spectrum softens in the high state. ACIS and SIS light curves (Fig. 1) show a similar timescale of variability.

Photon energy spectra of PG 1404+226 and associated background spectra were accumulated from the EPIC-PN, ASCA-SIS, and Chandra-ACIS data. The pulse invariant channels were grouped such that each bin contains at least 20 counts. Data above 8 keV are not used in spectral analysis because background counts are comparable with source counts in this regime. All the spectral fits were performed with the XSPEC version 11.2.0 and using the χ² statistics. The quoted errors on the best-fit model parameters are at the 90% confidence level (Δχ² = 2.7). Luminosities are derived assuming isotropic emission. A value for the Hubble constant of 70 km s⁻¹ Mpc⁻¹ and a standard cosmology with H₀ = 50 km s⁻¹ Mpc⁻¹ and a standard cosmology with H₀ = 50 km s⁻¹ Mpc⁻¹ has been adopted.

We fitted a redshifted power-law model with a Galactic N_H of 2 × 10²⁰ cm⁻² (Elvis et al. 1989) to the EPIC-PN spectrum in the energy range of 2–8 keV. This provides an acceptable fit (χ² per degree of freedom [dof] of ≈26/24 and Γ ~ 1.72). There is an excess emission above 6.5 keV, but addition of a narrow redshifted Gaussian line near 6.4 keV does not improve the fit (Δχ² < 4). Extrapolation of the best-fitting 2–8 keV power law to 0.3 keV shows a huge soft excess in the spectrum. Adding a redshifted blackbody gives a reasonable fit (χ²/dof ~ 189/162, Γ ~ 1.46, and kT_bb ~ 108 eV). The model (model a in Fig. 3) leaves significant residuals in the 0.8–1.2 keV (observed frame) band and at 3 keV. Addition of Gaussian absorption lines at 1, 1.2, and 3 keV to the previous model (hereafter model e) gives a good fit with χ²/dof ~ 134/156 (Fig. 2). All the derived parameter values along with the errors are given in Table 1. We have fitted several other models to the data based on the previous results reported on the same source (Fig. 3). An absorption component (model ABSORI in XSPEC) along with the blackbody and power law does improve the fit (χ²/dof ~ 154/158), but the absorption feature still remains (model b). Overabundance of iron (U99) cannot handle the absorption feature completely (χ²/dof ~ 154/159; the iron abundance became more than 25 times solar abundance). Adding an edge with the absorption model (with super iron abundance) does not improve the fit (Δχ² ~ 2). Adding an edge at ~1 keV with the two-component model (model c) can handle the absorption feature at 1 keV (χ²/dof ~ 153/160), but the 1.2 keV feature still remains. But adding another edge (model d) for the ~1.2 keV feature worsens the fit (Δχ² ~ 1). One edge and one line also cannot handle the situation. But when we adopt the model with two absorption lines, the fit is improved drastically (χ²/dof ~ 144/158) and the residuals around 1 keV vanished. Adding another absorption line at ~3 keV improves the fit further (Δχ² ~ 10).

To investigate whether the flux variability is due to changes in the spectral parameters, we have carried out spectral analysis at low- and high-flux levels. We extracted two average spectra covering 0–6.5 ks (high-flux state) and 9.5–15.5 ks (low-flux state) in the 0.3–8 keV band. The average EPIC-PN count rates are 0.26 ± 0.01 s⁻¹ (low-flux state) and 0.69 ± 0.02 s⁻¹ (high-flux state). We fit the data using model e. The fit parameters and the observed fluxes in the two flux states are given in Table 1. The observed flux in the 0.3–8.0 keV range varied by a factor of 2.6 during the high- and low-flux states. The blackbody flux varied by a factor of 3, whereas the power-law flux varied by a factor of 1.7. The spectral parameters are consistent with each other at 90% confidence level. Since the spectral parameters and the normalizations are strongly coupled to each other, we can only conclude that the soft and hard components varied at different ratios. The absorption lines, on the other hand, are not required at the low-flux level. We have included two lines (0.99 and 1.17 keV) to get an estimate of the upper limits to the fluxes. The 90% confidence upper limits on the line fluxes during the low-flux state are distinctly lower than those found for the high-flux state. The upper limit on the equivalent width (EW) has an overlap with the 90% confidence error for that in the high-flux level. To understand the spectral variability in more detail, we plot the pulse-height analyzer
(PHA) ratio of high- and low-flux states with energy (Fig. 2, inner panel). While the flux difference in the soft emission is remarkable, the variability above 1 keV is much lower. There is a clear dip at around 1 keV indicating that absorption is significantly high in the high-flux state.

To corroborate these findings, we have analyzed the spectra from the Chandra and ASCA data. The detection significance above 1 keV in these two data sets is poor, and we find marginal evidence of the absorption lines in the time-averaged data.

Results of the spectral fits to the high-flux states in these two data sets (marked in Fig. 1) are presented in Table 1. The absorption lines are detected in the ASCA data ($\Delta \chi^2 \sim 10$), and there is a marginal evidence of these lines in the Chandra data. The line energies and identifications in case of ASCA data are different from that by Leighly et al. (1997), probably because of different continuum modeling.

The strength of the absorption lines increased when the flux was significantly high in the high-flux state.

Table 1

| Component      | Parameter | EPIC-PN$^a$ | ASCA-SIS$^b$ | Chandra-ACIS$^c$ |
|----------------|-----------|-------------|--------------|------------------|
|                |           | Average     | High         | Low             | High            | High            |
| Blackbody      | $kT$ (eV) | 114$^{+2}_{-2}$ | 112$^{+2}_{-1}$ | 119$^{+2}_{-1}$ | 120$^{+2}_{-2}$ | 125$^{+1}_{-2}$ |
|                | $n_{e}$   | 2.97$^{+0.09}_{-0.08}$ | 4.34$^{+0.17}_{-0.17}$ | 1.33$^{+0.09}_{-0.10}$ | 7.46$^{+0.43}_{-0.40}$ | 2.66$^{+0.31}_{-0.37}$ |
|                | $f_{ph}(0.3-8 \text{ keV})$ | 10.33 | 14.82 | 4.86 | 25.82 | 11.05 |
| Power law      | $\Gamma$  | 1.59$^{+0.11}_{-0.12}$ | 1.67$^{+0.46}_{-0.46}$ | 1.27$^{+0.27}_{-0.30}$ | 1.95$^{+0.43}_{-0.42}$ | 1.55$^{+0.64}_{-0.65}$ |
|                | $n_{e}^1$ | 4.42$^{+1.32}_{-1.28}$ | 5.05$^{+2.30}_{-2.70}$ | 1.97$^{+1.60}_{-2.00}$ | 37.1$^{+15.1}_{-13.5}$ | 7.23$^{+1.15}_{-0.99}$ |
| Gaussian 1     | $E_{\text{inc}}$ (keV) | 3.07$^{+0.06}_{-0.04}$ | 3.03$^{+0.10}_{-0.12}$ | ... | ... | ... |
|                | $n_{e}$   | $-2.80^{+1.16}_{-1.22}$ | $-4.00^{+2.98}_{-2.78}$ | ... | ... | ... |
|                | EW (eV)   | $-348^{+394}_{-180}$ | $-438^{+328}_{-105}$ | ... | ... | ... |
| Gaussian 2     | $E_{\text{inc}}$ (keV) | 1.17$^{+0.02}_{-0.02}$ | 1.17$^{+0.03}_{-0.02}$ | 1.17 | 1.59$^{+0.10}_{-0.08}$ | 1.16$^{+0.06}_{-0.16}$ |
|                | $n_{e}$   | $-6.67^{+2.13}_{-2.05}$ | $-12.43^{+3.76}_{-3.36}$ | $>-4.80$ | $-15.7^{+12.3}_{-12.2}$ | $>-11.76$ |
|                | EW (eV)   | $-60^{+19}_{-18}$ | $-84^{+28}_{-25}$ | $-22^{+22}_{-27}$ | $-87^{+37}_{-47}$ | $-17^{+37}_{-37}$ |
| Gaussian 3     | $E_{\text{inc}}$ (keV) | 1.00$^{+0.04}_{-0.02}$ | 1.00$^{+0.04}_{-0.02}$ | 0.99 | 1.24$^{+0.03}_{-0.04}$ | 1.02$^{+0.10}_{-0.10}$ |
|                | $n_{e}$   | $-13.00^{+2.03}_{-2.03}$ | $-23.55^{+6.62}_{-6.62}$ | $>-9.30$ | $-35.8^{+20.8}_{-20.8}$ | $-13.1^{+12.0}_{-12.0}$ |
|                | EW (eV)   | $-44^{+17}_{-17}$ | $-59^{+16}_{-16}$ | $-23^{+32}_{-32}$ | $-81^{+27}_{-28}$ | $-28^{+28}_{-28}$ |
| Total          | $f_{ph}(0.3-8 \text{ keV})^d$ | 12.44 | 16.93 | 6.52 | 40.25 | 15.04 |
|                | $f_{ph}(0.3-8 \text{ keV})^d$ | 15.18 | 20.88 | 7.76 | 46.58 | 17.57 |
|                | $L_{\text{ph}}(0.3-8 \text{ keV})^d$ | 0.68 | 0.95 | 0.35 | 2.11 | 0.80 |
| $\chi^2$       | $\chi^2/\text{dof}$ | 134/156 | 101/119 | 85/88 | 29/38 | 31/63 |
|                | $\chi^2_{\text{H}}/\text{dof}$ | 144/158 | 107/121 | ... | ... | ... |
|                | $\chi^2_{\text{L}}/\text{dof}$ | 170/160 | 140/123 | 85/88 | 33/40 | 32/65 |
|                | $\chi^2_{\text{H}}/\text{dof}$ | 189/162 | 162/125 | 85/88 | 39/42 | 34/67 |

$^a$ Parameter values for EPIC PN, ASCA-SIS, and Chandra-ACIS data.
$^b$ Blackbody normalization in units of $10^{15}$ ergs s$^{-1}$ cm$^{-2}$ s$^{-1}$.
$^c$ Flux in units of $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$.
$^d$ Power-law normalization in units of $10^{-5}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV.
$^e$ Gaussian normalization in units of $10^{-4}$ photons cm$^{-2}$ s$^{-1}$.
$^f$ Source luminosity in units of $10^{44}$ ergs s$^{-1}$.
$^g$ $\chi^2$: excluding Gaussian 1; $\chi^2_{\text{H}}$: excluding Gaussian 1 and 2; $\chi^2_{\text{L}}$: excluding all Gaussian lines.
Absorption Lines Identified in the Parametric Fit to the Spectrum of PG 1404+226

| $E_{\text{meas}}$ | EW | $\Delta\chi^2$/dof | Instrument | $E_{\text{lab}}$ | Line | Velocity (km s$^{-1}$) |
|------------------|----|---------------------|------------|-----------------|------|-----------------------|
| 1.00$^{+0.02}_{-0.02}$ | $-46^{+17}_{-25}$ | 18/119 | EPIC-PN | 0.921 | Ne $\text{ix} \ 1s-2p$ | $25,700^{+300}_{-300}$ |
| 1.17$^{+0.02}_{-0.02}$ | $-61^{+16}_{-16}$ | 17/117 | EPIC-PN | 1.022 | Ne $x$ Ly$\alpha$ | $43,500^{+200}_{-200}$ |
| 1.24$^{+0.04}_{-0.04}$ | $-81^{+17}_{-16}$ | 6/40 | ASCA-SIS0 | 1.073 | Ne $\text{ix} \ 1s-3p$ | $27,000^{+200}_{-200}$ |
| 1.59$^{+0.10}_{-0.10}$ | $-87^{+9}_{-9}$ | 5/38 | ASCA-SIS0 | 1.47 | Mg $x$ii Ly$\alpha$ | $24,500^{+100}_{-100}$ |
| 3.07$^{+0.06}_{-0.06}$ | $-364^{+29}_{-38}$ | 10/154 | EPIC-PN | 2.62 | S $\text{xvi}$ Ly$\alpha$ | $51,500^{+100}_{-100}$ |

above (with C-statistics). All the parameters except the normalizations of blackbody, power-law, and absorption lines are fixed to the values found from the fit result of the average spectrum. The relative normalization between the absorption lines is kept fixed. The variation of the free parameters with time is shown in Figure 4. It is clear that all the free parameters vary with time in a same fashion and the variations are similar to the count rate variations. The blackbody flux is correlated with the line flux with a rank correlation coefficient of 0.79 (probability $8 \times 10^{-4}$).

3. DISCUSSION

The spectroscopic analysis carried out in this Letter using XMM-Newton data revealed three absorption-line features at $\sim$1.0, 1.17, and 3 keV with EW of 45, 60, and 364 eV, respectively. The line energy and EW are comparable to that found in PG 1211+143 by Pounds et al. (2003b). We have made similar identifications for the spectral lines detected in PG 1404+226, and they are given in Table 2. For some of the lines a few possible alternate line identifications are also given. For the two strongest lines detected by the EPIC-PN (0.99 and 1.17 keV) we derive outflow velocities of $25,700^{+300}_{-300}$ and $43,500^{+200}_{-200}$ km s$^{-1}$. However, if we consider that the 1.17 keV is originated from the line Ne $\text{ix} \ 1s-3p$ (1.07 keV), then the measured outflow velocity will be $27,000^{+200}_{-200}$ km s$^{-1}$. Although there is an indication of different velocities from the other line identifications, we cannot rule out the possibility of all lines originating from similar velocity structures because of the much lower significance level of detection of these lines.

The more striking result of our analysis is the possible detection of line variability. From the model-independent PHA ratio, we can see that there is strong spectral variability, and the absorption-line strength (EW) is also different in the two spectral states. The timescale of variation ($\sim$5000 s) suggests that the absorption features originate in the warm absorbing material located within $\sim$100 $R_g$ from the central source (for an estimated black hole mass of $5.2 \times 10^8 M_\odot$). Since it is unlikely that the physical condition of the absorbing material can change with the increase in the luminosity, we postulate that high luminosity drives stronger winds either because of radiation pressure or as a result of magnetic reconnection. The insufficient spectral resolution of the instrument leads to large uncertainty of the line energy. Uncertainty in the central energy, shape, and possible multiple absorption components in a single feature may lead to incorrect velocities or identifications. But in spite of these limitations, rapid variability of line strength is seen.

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