HIGHLY IONIZED IRON ABSORPTION LINES FROM OUTFLOWING GAS IN THE X-RAY SPECTRUM OF NGC 1365

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ABSTRACT

We present the discovery of four absorption lines in the X-ray spectrum of the Seyfert galaxy NGC 1365, at energies between 6.7 and 8.3 keV. The lines are detected with high statistical confidence (from >20 σ for the strongest to ~4 σ for the weakest) in two XMM-Newton observations 60 ks long. We also detect the same lines, with a lower signal-to-noise ratio (but still >2 σ for each line), in two previous shorter (~10 ks) XMM-Newton observations. The spectral analysis identifies these features as Fe xxv and Fe xxvi Kα and Kβ lines, outflowing with velocities varying between ~1000 and ~5000 km s⁻¹ among the observations. These are the highest quality detections of such lines so far. The high equivalent widths [EW(Kα) ~ 100 eV] and the Kα/Kβ ratios imply that the lines are due to absorption of the AGN continuum by a highly ionized gas with column density $N_H \sim 5 \times 10^{23}$ cm⁻² at a distance of ~(50–100)R_G from the continuum source.

Subject headings: galaxies: active — galaxies: individual (NGC 1365) — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

Warm absorbers are common among active galactic nuclei (AGNs). About half of the X-ray spectra of local bright Seyfert galaxies show evidence of a warm absorber with column densities in the range $10^{22}$–$10^{23}$ cm⁻² (e.g., Reynolds 1997). High-resolution grating observations performed with Chandra and XMM-Newton have shown that the warm absorber has a typical temperature of ~10⁶ K and, in some cases, outflowing velocities of a few times $10^3$ km s⁻¹ (Sako et al. 2001; Kaspi et al. 2002; Krongold et al. 2003). Recently, more extreme, “hot” absorbers have been discovered through the observation of H-like and He-like iron absorption lines in several AGNs (e.g., in NGC 3783: Kaspi et al. 2002, Reeves et al. 2004; in PG 1115+080: Chartas et al. 2003; in PG 1211+143: Pounds et al. 2003; in MCG –6-30-15: Young et al. 2005).

Here we report the discovery of four strong absorption lines in each of four XMM-Newton observations of the Seyfert galaxy NGC 1365, in the 6.7–8.3 keV band, which we identify as Fe xxv and Fe xxvi Kα and Kβ lines. NGC 1365 ($z = 0.0055$; de Vaucouleurs et al. 1992) is an X-ray–absorbed Seyfert galaxy, with a 2–10 keV flux of the order of (0.5–2) ergs s⁻¹ cm⁻² (Risaliti et al. 2000, 2005, hereafter R05), which shows extreme X-ray variability: changes from reflection-dominated to transmission-dominated states are observed on timescales as short as 3 weeks (R05). When in a transmission-dominated state, the measured cold column density varies between ~1 among the observations. These are the highest quality detections of such lines so far. The high equivalent widths [EW(Kα) ~ 100 eV] and the Kα/Kβ ratios imply that the lines are due to absorption of the AGN continuum by a highly ionized gas with column density $N_H \sim 5 \times 10^{23}$ cm⁻² at a distance of ~(50–100)R_G from the continuum source.

2. DATA ANALYSIS AND RESULTS

Two XMM-Newton (Jansen et al. 2001) observations of 60 ks each were obtained in 2003 December and 2004 July. Two shorter (~10 ks) observations were obtained earlier in 2003. A spectral analysis of all these observations showed the source to be in a transmission-dominated state (R05). The observation log is reported in Table 1, together with the main parameters of the continuum fit, which are described in § 3.

We reduced the EPIC pn and MOS data using the SAS 6.0 package. We extracted a spectrum from a circular region of 30″ radius and the background from nearby regions free from bright serendipitous sources. In all cases, the background counts are negligible at all energies (on average ~2% of the signal). In particular, we checked that no narrow background line is present in the energy range that is most crucial for our analysis, i.e., between 6.7 and 8.3 keV, where the absorption lines are detected. The data obtained with the two MOS arrays were merged. Calibration matrices were computed for each spectrum. We rebinned the spectra in order to have at least 20 counts bin⁻¹. This allows us to use χ² minimization in the model fitting.

For all four spectra, a good fit is obtained with a model consisting of an absorbed power law with $N_H$ between 1 and $5 \times 10^{23}$ cm⁻² plus a cold reflection component (using the PEXRAV model in XSPEC; Magdziarz & Zdziarski 1995) and a narrow emission line at 6.4 keV. At energies below the photoelectric cutoff, a thermal emission component dominates, with $K T \sim 0.8$ keV (R05). A broad emission line, probably relativistic, is also needed to properly fit the 4–6 keV region. In addition to these “standard” components, four absorption lines in the energy range 6.7–8.3 keV are strongly requested by the fit. A complete analysis of the emission spectrum of NGC 1365 will be presented elsewhere, together with a detailed study of the spectral variability during the two long observations. Here we concentrate on the most striking features in these spectra, i.e., the group of absorption lines present in the 6.7–8.3 keV spectral region. In order to visually show the relevance of these lines, in Figure 1 we plot the 5–10 keV residuals to a thermal reflection model with the same components as above, except for the four absorption lines, and fitted ignoring the energy ranges 6.7–7.2 and 7.8–8.3 keV. The spacing of the lines strongly suggests that they are Fe xxv and Fe xxvi Kα and Kβ.

Accordingly, in the global 0.5–10 keV fits, the four lines were fitted with narrow Gaussians, with free energies allowed to vary.
from the oscillator strength ratios. Ratios (Table 3) are significantly smaller than those expected discussed in detail in a forthcoming paper.

tinuum parameters, listed in Table 1, are typical of X-ray spectra observations, with three fewer free parameters.

but vary among the different observations from ∼1000 to ∼5000 km s⁻¹.

3. The Kea/Kβ ratios are much smaller than the theoretical oscillator strength values (Table 3) and are consistent with staying constant between the observations.

In the following, we discuss the composition (ionization state, column density), the geometrical structure, and the origin of the hot absorber.

Composition.—The low Kea/Kβ ratios can only be explained if saturation effects are significant. Any other physical expla-

3. DISCUSSION

The main results of our spectral analysis are the following:

1. We detected four absorption lines in the energy range 6.7–8.3 keV in four XMM-Newton observations of NGC 1365, with equivalent width in the 50–150 eV range. We identified these lines as Fe xxv and Fe xxvi Ke and Kβ.

2. In all observations, the lines are blueshifted. Blueshift velocities are the same for all lines in the same observation for each single line and each single fit. All four lines are significantly detected in all spectra, except in two cases where the detection is marginal (Fe xxv Kβ in OBS 1 and OBS 2). For the two highest quality observations, OBS 3 and OBS 4, the fits were performed on pn and MOS data separately.

Since the best-fit energies are close to those of the four lines mentioned above, we estimated the blueshift/redshift velocities corresponding to the differences between the measured and theoretical energies for these lines. The velocities are shown in Figure 2. In both observations, the results are in agreement with a common outflow velocity for the four lines. Therefore, we performed a new fit, fixing the energies of the four lines to the theoretical values (taking into account the redshift of the source) and allowing for a single free redshift/blueshift. We obtained as good a fit as in the previous case, where all the lines were left free (∆χ² < 8 in the global fit in all observations, with three fewer free parameters).

The best-fit line parameters are listed in Table 2. The continuum parameters, listed in Table 1, are typical of X-ray spectra of obscured, Compton-thin Seyfert galaxies and will be discussed in detail in a forthcoming paper.

In Figure 3, we show the 5–10 keV spectrum and best-fit model for the two long observations. The measured Kea/Kβ ratios (Table 3) are significantly smaller than those expected from the oscillator strength ratios.

In all four spectra, the lines are blueshifted with respect to the expected theoretical line energy peaks. The velocity shifts are between 1000 and 5200 km s⁻¹ (Table 2) and are statistically highly significant, except for the first observation, where the data are in agreement with zero velocity. The differences between the outflow velocities are highly significant and cannot be due to instrumental effects. In order to check the reality of this shift, we compared the low-energy thermal emission lines in the ~1 keV region (which are expected to be constant, given the good signal-to-noise ratio and the extent of the thermal emission region resolved by Chandra; R05) and found that they overlap perfectly (∆(E) < 10 eV).

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3. Throughout this Letter, we refer to the atomic physics values of the NIST atomic database (http://physics.nist.gov) and reported in Table 1 of Bianchi et al. (2005, hereafter B05).
can be obtained with cm\( G \) observations of NGC 1365. The background spectrum is shown with XMM-Newton (for an ionizing continuum with ).

One first introduced by Netzer (1996). For ease of comparison, if \( \log U_\alpha \) responds to velocities of \( \pm 15 \) km s\(^{-1}\), the ionization parameter defined as has a value 1.17.

With the available statistics, we find that the minimum detectable velocity is of the order of 2000 km s\(^{-1}\). Therefore, no useful constraint on \( v_i \) can be obtained from our fits.

We calculated the curve of growth for the K\( \beta \) lines using the same model as B05. In order to have a precise estimate of the outflowing velocity of the absorbing gas.\( ^a \)

EW ratios, we also considered the contribution of the Fe xxv K\( \gamma \) line at 8.29 keV, which is blended with the Fe xxvi K\( \beta \) in low-resolution spectra and has an oscillator strength about half of that of the Fe xxvi K\( \beta \). A further minor contribution could come from the Ni xxvii (He-like) K\( \alpha \) at 7.98 keV. Its oscillator strength is 0.19 that of Fe xxv K\( \beta \). An overabundance of nickel could make this contribution important. However, we note that in this case the line profile would be significantly altered, given that the energy separation between the two lines (\( \Delta E \approx 80 \) eV) is comparable to the EPIC resolution (~150 eV for both pn and MOS cameras; but note that with the high statistics available the peak energies of the lines are determined with a much better precision, ~10–15 eV). This is not observed (Fig. 1). We conclude that the contribution of nickel lines cannot be significant.

The above estimates are computed adopting a fixed ionization is ruled out, since (1) the theoretical ratio is well established, since it involves transitions to the fundamental level in relatively simple (He-like and H-like) atomic species, and (2) the energy difference between the lines is too small for the continuum slope to play a significant role: for a photon index \( \Gamma = 2.0 \), we have \( F_\gamma(6.7 \text{ keV})/F_\gamma(7.9 \text{ keV}) = 1.17 \). Following B05, an equivalent width of the K\( \alpha \) lines \( EW \sim 100–150 \) eV can be obtained with \( N_\| > 10^{23} \) cm\(^{-2}\), a turbulent velocity of the absorbing gas \( v_i = 1000 \) km s\(^{-1}\), and an ionization parameter \( \log U_\alpha = 0 \).\( ^a \) We note that the EPIC resolution at 8 keV corresponds to velocities of \( \sim 5000 \) km s\(^{-1}\). With the available statistics, we find that the minimum detectable velocity is of the order of 2000 km s\(^{-1}\). Therefore, no useful constraint on \( v_i \) can be obtained from our fits.

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| Line       | OBS 1       | OBS 2       | OBS 3       | OBS 4       |
|------------|-------------|-------------|-------------|-------------|
|            | \( E \) (keV) | \( EW \) (eV) | \( \Delta(\chi^2) \) | \( EW \) (eV) | \( \Delta(\chi^2) \) | \( EW \) (eV) | \( \Delta(\chi^2) \) | \( EW \) (eV) | \( \Delta(\chi^2) \) |
| Fe xxv K\( \alpha \) | \( 6.697 \) | \( 110^{+66}_{-30} \) | 17 | 135 ± 30 | 30 | 120 ± 20 | 173 | 154 ± 20 | 264 |
| Fe xxvi K\( \alpha \) | \( 6.966 \) | \( 94 \pm 50 \) | 11 | 111 ± 30 | 20 | 104^{+15}_{-20} | 52 | 145^{+15}_{-20} | 167 |
| Fe xxv K\( \beta \) | \( 7.880 \) | \( 81 \pm 55 \) | 5 | 100 ± 60 | 6 | 93 ± 10 | 43 | 108 ± 20 | 60 |
| Fe xxvi K\( \beta \) | \( 8.268 \) | \( 127 \pm 60 \) | 12 | 130 ± 60 | 10 | 80 ± 15 | 18 | 110 ± 25 | 59 |
| \( V \) (km s\(^{-1}\)) | \( 1000^{+1000}_{-100} \) | \( 2000^{+400}_{-400} \) | \( 2500^{+400}_{-400} \) | \( 5200^{+400}_{-400} \) |

* Errors are at a 90% confidence level.
* \( \Delta(\chi^2) \) with respect to the best-fit model without the four absorption lines. The four lines are forced to have the same blueshift, so the model including the lines has five more parameters than the no-line model.
* The Fe xxvi K\( \beta \) line is blended with the Fe xxv K\( \gamma \) line (see text for details).

![Figure 3](image1.png)  
**Fig. 3.**—Hard X-ray (5–10 keV) spectra and best-fit model for the two long XMM-Newton observations of NGC 1365. The background spectrum is shown for each observation. [See the electronic edition of the Journal for a color version of this figure.]

![Figure 4](image2.png)  
**Fig. 4.**—Left panels: Curves of growth for the Fe xxv and Fe xxvi K\( \alpha \) lines, for \( \log U_\alpha = 0 \). Right panels: K\( \alpha \)/K\( \beta \) ratios for Fe xxv and Fe xxvi. The shaded regions are the 90% confidence intervals for the averages obtained from the four observations. [See the electronic edition of the Journal for a color version of this figure.]
ization parameter $U_X$. Therefore, we expect that they slightly change for different choices of $U_X$. However, we do not expect to find acceptable solutions for significantly lower or higher ionization parameters: if (1) $\log U_X > 0$, the iron atoms are almost completely stripped, making it impossible to obtain as high EWs as observed; if (2) $-1 < \log U_X < 0$, the He-like Fe atoms are overabundant with respect to the H-like ones, because the ionizing continuum is enough to strip all the L shell electrons but not to strip the two inner electrons. The ratio between Fe xxv and Fe xxvi lines would then be much higher than observed. This argument is discussed in more detail in B05.

The turbulent velocity is significantly higher than the thermal velocity of a gas with the same ionization state ($\sigma_v \sim 100–200 \text{ km s}^{-1}$). As a consequence, the line widths probably indicate true bulk motions. These might be related to the observed changes in outflow velocity.

**Geometrical properties.**—The high ionization parameter required to explain the line ratios can be used to put constraints on the distance of the line absorber from the X-ray continuum source, assuming that the ionization state is due to UV radiation from the central source rather than to a high thermal temperature of the gas. For $\log U_X = 0$, $N_H = 5 \times 10^{23} \text{ cm}^{-2}$, and a $2-10$ keV photon index $\Gamma = 2$, we obtain $R \sim 2 \times 10^{15}(\Delta R/R)_{U_X}$ cm, where $L_{\text{bol}}$ is the 2–10 keV luminosity in units of $10^{42}$ ergs s$^{-1}$ (Table 1) and $\Delta R$ is the thickness of the absorber along the radial direction; $R$ is the average distance of the absorber, so we expect $\Delta R/R \sim 1$. We note that a distance of $\sim 10^{15}$ cm is of the order of what a gas with a velocity $v \sim 4000 \text{ km s}^{-1}$ (intermediate between the two measurements in the last two observations, OBS 3 and OBS 4) would cover in $\sim 6$ months between OBS 3 and OBS 4 ($\sim 2 \times 10^7$ s). This is in qualitative agreement with our assumption of an absorbing gas with a thickness of the same order of the distance from the central source. A smaller thickness ($\Delta R/R < 1$) would imply an even smaller distance from the central source.

**Origin.**—The short distance inferred from the high ionization state of the absorber and the rough black hole mass estimate ($M_{\text{BH}} \sim 10^5 M_\odot$; R05) imply that the gas is located at the radii of the accretion disk, $\sim 50(M/M_\odot)^{-1}$ Schwarzschild radii from the black hole. Hot gas could be present in this region either as the external part of the hot corona believed to be responsible for the X-ray emission in AGNs (e.g., Haardt & Maraschi 1991) or as the inner part of a wind arising from the disk (Murray & Chiang 1995; Proga et al. 2000).

We note that the observed blueshift velocity is smaller than the escape velocity at $50(M/M_\odot)^{-1}R_s$, which is of the order of about $50,000(M/M_\odot)^{-0.5} \text{ km s}^{-1}$. However, the observed velocity is of the order of that predicted in the vertical part of the funnel-shaped wind of Elvis (2000). The main problem with the wind scenario is that radiation force is not an effective acceleration mechanism in our case, since the gas is ionized (so line absorption is not an efficient way to exchange momentum from radiation to gas) and the bolometric luminosity (of the order of a few times $10^{43}$ ergs s$^{-1}$, adopting a standard X-ray to bolometric correction; Risaliti & Elvis 2004) is a small fraction of the Eddington luminosity, $L_{\text{Edd}} \sim 2 \times 10^{46}(M/M_\odot)^{-1}$ ergs s$^{-1}$, making Thomson scattering acceleration negligible with respect to gravity. However, two mechanisms could provide the observed highly ionized gas: (1) a poloidal magnetic field could effectively extract the gas from the accretion disk and form a wind (Blandford & Payne 1982; Konigl & Kartje 1994), and (2) gas arising from the accretion disk due to local instabilities would be ionized by the central UV/X-ray source and initially expand toward the vertical direction (with respect to the disk plane) due to its internal pressure. The gas would then fail to form a wind if no external force is present, but a fraction of the line of sight, at small angles with respect to the disk plane, would be covered by such gas, with the required ionization state and column density and with a (temporary) outflowing velocity of the order of a few times $10^3 \text{ km s}^{-1}$. Similar properties are predicted for the inner “hitchhiking gas” in radiation-driven wind models (Murray & Chiang 1995).

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We refer the reader to the references in Table 1. Theoretical ratios are given in Table 3.

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### Table 3: Fe xxv and Fe xxvi Kα/Kβ Ratios

| Line       | OBS 1  | OBS 2  | OBS 3  | OBS 4  | $R_9^{-1}$ | Theoretical $b$ |
|------------|--------|--------|--------|--------|------------|-----------------|
| Fe xxv     | 1.4 ± 1.7 | 1.4 ± 1.1 | 1.4 ± 0.4 | 1.4 ± 0.4 | 1.4 ± 0.3 | 5.0             |
| Fe xxvi    | 0.7 ± 0.7 | 0.9 ± 0.6 | 1.4 ± 0.7 | 1.3 ± 0.4 | 1.1 ± 0.3 | 3.2             |

*a* Average ratios.  
*b* Oscillator strength ratios. In R2, the contribution of Fe xxv Kγ has been taken into account.

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