EVIDENCE OF ABSORPTION DUE TO HIGHLY IONIZED GAS IN THE RADIO-QUIET QUASAR PG 1114+445
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ABSTRACT
We present results on the X-ray spectrum of the quasar PG 1114+445 from an ASCA observation performed in 1996 June and a ROSAT observation performed 3 years earlier. We show that good agreement between all the data sets can be obtained if the underlying continuum in the 0.2–10 keV band is assumed to be a power law (photon index $\Gamma \approx 1.8$) absorbed by photoionized material. The ionized gas imprints deep absorption edges in the observed spectrum $\lesssim$2 keV due to O vii and O viii, from which we determine its column density ($\sim 2 \times 10^{22}$ cm$^{-2}$) and ionization parameter ($U_X \sim 0.1$) to be similar to that observed in Seyfert 1 galaxies. Unfortunately, these data do not allow any strong constraints to be placed on the location of or the solid angle subtended by the material at the ionizing source. We also find evidence of absorption in the Fe K-shell band in excess of that predicted from the lower energy features. This implies an Fe/O abundance ratio $\sim 10$ times the cosmic value, or an additional screen of more highly ionized gas, possibly outflowing from the nucleus. We briefly compare our results with those obtained from other active galaxies.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — quasars: individual (PG 1114+445) — X-rays: galaxies

1. INTRODUCTION
A number of ROSAT and ASCA X-ray observations of low-luminosity active galactic nuclei (AGNs) have shown clear evidence of absorption by highly ionized gas along the line of sight (e.g., Nandra & Pounds 1992; Turner et al. 1993; Reynolds 1997; George et al. 1998 and references therein). The presence of such gas is revealed primarily by the O vii and O viii absorption edges imprinted on the underlying continuum. Recent studies show that the ionized gas generally has a relatively large column density (corresponding to effective hydrogen column densities $N_H \sim 10^{21}$–$10^{23}$ cm$^{-2}$, although there are obvious selection effects due to the bandpasses and sensitivities of the instruments) and exists in $\sim$ 50%–75% of Seyfert 1 galaxies (Reynolds 1997; George et al. 1998, hereafter G98).

The situation in the case of higher luminosity AGNs is less clear. Recent studies have shown that a large fraction of radio-loud quasars (RLQs) show evidence of intrinsic absorption (Cappi et al. 1997). The ionization state of the material generally cannot be determined from current data, although there is strong evidence that it is highly ionized in at least two cases (3C 351, Fiore et al. 1993; 3C 273, Grandi et al. 1997). Interestingly, intrinsic absorption appears to be far less common in radio-quiet quasars (RQQs), which are thought to make up $\sim 90\%$ of the total quasar population (Laor et al. 1997; Fiore et al. 1998). Indeed, there are only two cases documented to date: MR 2251–178 (Halpern 1984; Pan, Stewart, & Pounds 1990; Mineo & Stewart 1993) and IRAS 13349+2438 (Brandt, Fabian, & Pounds 1996). Such a difference between the two classes could be taken to mean that gas does not exist along the line of sight in RQQs. Alternatively, a substantial column density of gas could be present but so highly ionized as to be transparent in the X-ray band, or the absorption features imprinted by such gas could be swamped by continuum photons arriving via another (transparent) travel path.

PG 1114+445 ($z = 0.144$; Schmidt & Green 1983) is an RQQ with $L_{\text{UV}} \sim 10^{45}$ ergs s$^{-1}$, lying in a direction of relatively low Galactic line-of-sight column density ($N_{\text{HI}}^\text{Gal} = 1.94 \times 10^{20}$ cm$^{-2}$ from the 21 cm measurements of Murphy et al. 1996). These characteristics led to the inclusion of the source as one of 23 quasars forming the complete sample of the Bright Quasar Survey, studied by the Position Sensitive Proportional Counter (PSPC) on ROSAT (Laor et al. 1997).

Interestingly, PG 1114+445 was one of the few objects whose PSPC spectrum could not be adequately modeled by a single power law and the only object for which there was strong evidence of absorption by ionized material (Laor et al. 1994). Further evidence of absorption by ionized material comes from a recent Hubble Space Telescope observation that has revealed UV absorption lines at C iv, N v, and Ly$\alpha$ (Mathur 1997). Here we present the results from a follow-up ASCA observation of PG 1114+445, along with a reanalysis of the PSPC data.

2. OBSERVATIONS AND DATA REDUCTION
The new observation reported here was performed using ASCA on 1996 May 6–7. The ASCA satellite (Makishima et al. 1996) consists of four identical, co-aligned X-ray telescopes (XRTs; Serlemitsos et al. 1995). Two solid-state imaging spectrometers (SISO and SIS1), each consisting of four CCD chips, sit at the focus of two of the XRTs and provide coverage over the $\sim 0.4$–10 keV band (Burke et al. [1997]).
ABSORPTION BY HIGHLY IONIZED GAS IN PG 1114 + 445

1994). Two gas imaging spectrometers (known as GIS2 and GIS3) sit at the focus of the other two XRTs and provide coverage over the ~0.8–10 keV band (Ohashi et al. 1996 and references therein). The observation reported here was carried out in 1-CCD mode with the target in the nominal pointing position. The data collected in FAINT and BRIGHT telemetry modes were combined. We applied the same data selection criteria and data analysis methods to the ASCA data as presented in Nandra et al. (1997a), using the FTOOLS/XSELECT package (versions 3.5 and 3.6). Combined, these gave rise to (5–7) × 10^4 s of useful data in each of the detectors, from which we derive mean source count rates of (4.5 ± 0.1) × 10^{-2} counts s^{-1} and (3.4 ± 0.1) × 10^{-2} counts s^{-1} in the SIS0 and GIS2 detectors, respectively, and similar rates in SIS1 and GIS3. The total number of source photons detected in each instrument was (2–3) × 10^5. We find no significant variability on timescales <~90 minutes, and only marginal evidence of changes in flux on longer timescales.

We have also independently analyzed the ROSAT PSPC observation of PG 1114 + 445 presented by Laor et al. (1994), having obtained the data from the archive. This observation was carried out on 1993 June 6–7, and using standard data selection and reduction techniques gives rise to 7 ks of useful data and a mean source count rate of (10.2 ± 0.4) × 10^{-2} counts s^{-1}. No significant variability was observed.

A number of serendipitous sources are apparent within the field of view of ROSAT, at least one of which is also detected by the ASCA GIS, but at sufficiently large angular distances not to affect the analysis of PG 1114 + 445 presented here.

3. SPECTRAL RESULTS

Given the lack of strong variability during the observations, mean spectra were constructed for each detector, and it is the results from these that we concentrate on for the rest of the paper. As is common practice, in all cases we fitted the data from each detector simultaneously, but allowing the normalization of each to be a free parameter in order to allow for differences in the sizes of the extraction cell used, along with any discrepancies in the absolute flux calibration of the individual telescope/detector systems. The spectral analysis was performed using XSPEC (version 9.01; Arnaud 1996). Appropriate detector redistribution matrices were used (those released 1994 November 9 and 1995 March 6 for the ASCA SIS and GIS, respectively, and pscpbgain2_256.rmf for the ROSAT PSPC). The effective area appropriate for each data set was calculated using ASCAARF (version 2.5) for the ASCA data and PCARF (version 2.1.0) for the PSPC data. In the case of the SIS data, we have restricted our spectral analysis to energies ≥0.6 keV because of residual uncertainties in the calibration of the SIS/XRT instrument (see Dotani et al. 1996 and the information provided by the ASCA Guest Observer Facility at NASA/GSFC). However, while the calibration is suspect at these energies, it is considered unlikely to be in error by ≥20%. Thus, following G98 we have also calculated the weighted mean of the data-to-model residuals (R_{A,0}) when the best-fitting model is extrapolated below 0.6 keV. The rationale behind this parameter is that it allows us to identify models that are deemed acceptable above 0.6 keV but in which the extrapolation to energies below 0.6 keV is inconsistent with the suspected size of the calibration uncertainties.

The raw spectra extracted for each detector were grouped such that each resultant channel had at least 20 counts per bin, permitting us to use χ^2 minimization during the spectral analysis. This results in a total of 511 spectral bins for the combined ASCA detectors and 37 spectral bins for the PSPC data. In passing, we note that in the 0.6–0.8 keV band these grouped spectral bins are each typically 0.06 keV wide (for both the SIS and PSPC data sets). This is comparable to the spectral resolution of the SIS at the epoch of the observations (FWHM ≈ 0.09 keV) and far smaller than the spectral resolution of the PSPC (FWHM ≈ 0.35 keV) within this energy band. Appropriate background spectra were extracted from source-free regions of each detector.

We have compared a number of hypothetical models with the mean spectra. In all models considered here, we have assumed an underlying continuum represented by a single power law (of photon index Γ) throughout the 0.1–10 keV band (observer’s frame). All the models also include the effects of absorption by neutral material at z = 0 parameterized by an effective hydrogen column density N_{H,0} (assuming the abundances and cross sections of Morrison & McCammon 1983), which can be allowed to vary during the spectral analysis (but constrained to be ≥N_{H,0}^{gal}) Most models include an additional column density N_{HI} of absorbing material at the redshift of the source. Errors are quoted at 68% confidence limits for the appropriate number of interesting parameters (where all free parameters are considered interesting except the absolute normalization of the model).

3.1. Analysis of the Overall Continuum

3.1.1. Fits to the ASCA Data

We find that a simple power-law fit to the ASCA data in the 0.6–10 keV band confirms the presence of substantial absorption. If the absorbing material is assumed to be neutral, we find N_{H,0} ≈ 6 × 10^{21} cm^{-2} or N_{HI} ≈ 7 × 10^{21} cm^{-2}, depending whether the material is assumed to be local or at the redshift of the quasar. Both fits yielded a photon index Γ ≈ 1.6 and statistically acceptable fits (with reduced χ^2 value of χ^2 = 1.0). However, the extrapolation of both best-fitting models predicts fewer counts below 0.6 keV than observed by a factor R_{0.1−0.6} ≈ 14 and give rise to an increase in χ^2 statistic of Δχ^2 ≈ 70 (for six additional spectral bins). Such a discrepancy is far greater than can be accounted for by the remaining uncertainties in the instrumental calibration. As we shall see below, these solutions are artifacts of the presence of absorption by ionized gas.

Numerous elements have photoelectric absorption edges with threshold energies within the 0.6–1.0 keV band. However, for cosmic abundances, the opacity in this band is dominated by K-shell absorption by C, O, and Ne and L-shell absorption by Fe (see, e.g., Morrison & McCammon 1983). Given the redshift of PG 1114 + 445, the most significant edges likely to be observable in ASCA spectra are those due to O VII and O VIII, with rest-frame energies of 739

8 So as to include the Gaussian fudge factor, but not the filter fudge in the case of the SIS data sets. We have also compared our results with those obtained using several developmental versions of ASCAARF (up to and including version 2.64) but find no significant differences.
and 871 eV, respectively. Including such edges in our analysis (fixing $N_{\text{H},0} = N_{\text{H},1}\text{Gal}$ and $N_{\text{H},z} = 0$), we find optical depths in these species of $\tau(\text{O vii}) \approx 2.5$ and $\tau(\text{O viii}) \approx 1.1$. Such a model can be considered a crude parameterization of the absorption features imprinted by ionized gas along the line of sight to the nucleus. However, at such large optical depths absorption by other abundant elements is likely to be important also, and hence a more detailed treatment is required. Here we consider the case in which the material is ionized by the central continuum and employ theoretical spectra generated using the photoionization code ION (Netzer 1993, 1996, version ION95). The ionization state of the gas is parameterized by the “X-ray ionization parameter” $U_X$ (Netzer 1996; the ionizing radiation field is determined over the $0.1$–$10$ keV band). Further details about the assumptions made in the ION models and the method by which they were included in the spectral analysis can be found in G98.

We find that including the absorption by photoionized gas provides an excellent description of the ASCA data (with $N_{\text{H},0} = N_{\text{H},1}\text{Gal}$) yielding $\Gamma \approx 1.8$, $N_{\text{H},z} \approx 2 \times 10^{22}$ cm$^{-2}$, and $U_X \approx 0.1$ (Table 1, first row). The addition of $U_X$ as an additional free parameter is significant at greater than 99.9% confidence (F-statistic of 33.7). Furthermore, this model yields far better agreement with the ASCA data below 0.6 keV ($\overline{R}_{0.6} \sim 0.8$, consistent with the current uncertainties in the instrumental calibration). When such a model is assumed, we find $N_{\text{H},0}$ consistent with $N_{\text{H},1}\text{Gal}$, with an upper limit to any such excess absorption of $\Delta N_{\text{H},0} \approx 3 \times 10^{21}$ cm$^{-2}$ (Table 1, second row). The best-fitting model spectrum, along with the observed data-to-model ratios (for the $N_{\text{H},0} = N_{\text{H},1}\text{Gal}$ case) are shown in Figure 1, and the $\chi^2$ contours in $(N_{\text{H},0},U_X)$-space are shown (solid lines) in Figure 2. As can be seen from Figure 1, for the best-fitting values of $N_{\text{H},z}$ and $U_X$ the intervening gas imprints a series of absorption edges on the underlying continuum, dominated by C vii, O vii, and O viii. However, it should be noted that the ionization level of the gas is such that it becomes increasingly transparent as one moves to lower energies below the O vii edge (0.65 keV in the observer’s frame). It is this behavior that leads to a better agreement between the extrapolated model and the observed SIS data below 0.6 keV and, we suggest, with the PSPC data (see below). We have considered models in which the ionized absorber attenuates only a fraction of the underlying continuum. However, in all cases we find a covering fraction consistent with 100%, and thus such models are not considered further. Stringent constraints cannot be placed on the redshift of the ionized gas, $z_{\text{abs}}$, using the current data. However, we do find $z_{\text{abs}} > 0.103$ at 90% confidence, consistent with the systemic redshift of the host galaxy, and limiting the ionized gas to be in an outflow/wind of velocity $\lesssim 10^5$ km s$^{-1}$ relative to the nucleus.9

With the assumption that our line of sight is not uniquely privileged, we have also tested whether any useful constraints can be obtained on the solid angle $\Omega$ subtended by such gas at the central continuum source from its expected emission/scattering spectrum. However, the inclusion of such a component in the spectral analysis (where $N_{\text{H},z}$ and $U_X$ of the emitting gas are the same as those for the absorbing gas) is inconclusive. We find an upper limit on the strength of such a component that is expected from a full shell of such material ($\Omega = 4\pi$), assuming that it was irradiated by the continuum source with a luminosity $\lesssim 8$ times greater than that derived from the observations. This is hardly surprising given that by far the bulk of the emission expected from ionized gas in this region of $(N_{\text{H},z},U_X)$ parameter space occurs below the O vii edge and, hence, below 0.6 keV in the observer’s frame.

### 3.1.2. Fits to the ROSAT Data

Considering the PSPC data alone, we confirm the results of Laor et al. (1994) that a single power law does not provide an adequate description of the data (yielding $\chi^2$ per degree of freedom [dof] of 59.5/35) but that a statistically satisfactory fit can be obtained with the addition of a deep absorption edge. From our analysis, fixing $N_{\text{H},0} = N_{\text{H},1}\text{Gal}$, we find a best-fitting solution with an edge of optical depth $\tau = 3.5 \pm 1.1$ at an energy $E_\gamma = 0.77^{+0.05}_{-0.06}$ keV (in the rest frame of the quasar) imprinted on an underlying continuum with $\Gamma = 1.96^{+0.17}_{-0.12}$ and $\chi^2$/dof = 23.1/33. These values are in agreement with those found by Laor et al. (1994; $\tau \approx 3$ at $E_\gamma \approx 0.76$ keV), and with a blend of the O vii and O viii edges found in the analysis of the ASCA data. Repeating the analysis, but assuming the photoionization models

### TABLE 1

| $N_{\text{H},0}$ ($10^{21}$ cm$^{-2}$) | $N_{\text{H},z}$ ($10^{21}$ cm$^{-2}$) | $\log U_X$ | $\chi^2$/dof | $\Delta E_\gamma^{0.6}$ | $\overline{R}_{0.6}$ |
|---------------------------------|---------------------------------|-------------|--------------|----------------|----------------|
| 0.19 (f) ........... | 1.75 $^{+0.10}_{-0.10}$ | 19.60 $^{+4.39}_{-3.82}$ | $-1.027^{+0.110}_{-0.102}$ | 478/504 | 10.8 |
| 1.25 $^{+0.01}_{-0.01}$ (p) .... | 1.78 $^{+0.15}_{-0.12}$ | 21.03 $^{+11.13}_{-6.19}$ | $-0.877^{+0.724}_{-0.240}$ | 475/503 | 6.2 |
| Joint ASCA and ROSAT analysis: | | | | | |
| 0.22 $^{+0.01}_{-0.01}$ (p) .... | 1.79 $^{+0.12}_{-0.10}$ | 22.94 $^{+5.57}_{-4.28}$ | $-0.922^{+0.111}_{-0.084}$ | 508/539 | 31.6 |
| 0.19 (f) ........... | 1.76 $^{+0.07}_{-0.07}$ | 21.42 $^{+2.60}_{-2.64}$ | $-0.953^{+0.107}_{-0.103}$ | 508/540 | 23.0 |

**Notes:** Fits undertaken in the 0.6–10.0 and 0.1–2.0 keV bands in the observer’s frame for ASCA and ROSAT, respectively. $N_{\text{H},0}$ is the neutral column at $z = 0$ (constrained to be $\geq N_{\text{H},1}\text{Gal} = 1.94 \times 10^{20}$ cm$^{-2}$); $\Gamma$ is the photon index of the underlying power law continuum; $N_{\text{H},z}$ is the column density of the ionized gas at the redshift of the source; $U_X$ is the ionization parameter (see text); $\Delta E_\gamma^{0.6}$ is the increase in the $\chi^2$ statistic; and $\overline{R}_{0.6}$ is the mean data-to-model ratio when the best-fitting model is extrapolated to the six SIS spectral bins below 0.6 keV. The errors are at 68% confidence for three (first and third rows) and four (second and fourth rows) interesting parameters; (f) indicates the parameter was fixed at the specified value, and (p) that $N_{\text{H},0}$ was “pegged” at $N_{\text{H},1}\text{Gal}$.

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9 It should be noted that the spectral energy resolution of the ASCA SIS ($\Delta E/E \approx 0.14$ at the epoch of the observations) prevents the velocity distribution of the ionized gas from being constrained within $\sigma_v \lesssim 2 \times 10^4$ km s$^{-1}$. 
described above (with \( N_{H,0} = N_{H,0}^{\text{Gal}} \)) we find \( N_{H,0} = 37_{-22}^{+41} \times 10^{21} \) cm\(^{-2} \), \( U_X = 0.24_{-0.13}^{+0.11} \), and \( \Gamma = 1.7_{-0.3}^{+0.3} \) with \( \chi^2/\text{dof} = 22.7/33 \). These values are in good agreement with those obtained from the ASCA data above. However, despite the fact that the PSPC provides some data at energies below 0.6 keV, the low signal-to-noise ratio of these data, along with the relatively poor spectral resolution of the detector, leads to few additional constraints on the state of the ionized gas than provided by the PSPC data alone.

3.1.3. Joint Analysis of the ASCA and ROSAT Data

Here we present the results from a joint analysis of both the ASCA and ROSAT data sets, which may yield better constraints on the properties of the ionized gas. As above, the same spectral model is assumed for the data from each mission, but the normalization (only) of the underlying power law is allowed to vary in order to allow for any intensity variations in the source over the 3 years between the observations.

As expected, statistically acceptable results are obtained with the photoionization model (Table 1, third and fourth rows), with the flux during the ROSAT observation being ~90% of that at the time of the ASCA observations. This is close to the accuracy of the absolute flux calibration between the two instruments, so it is not significant. It can be seen that the best-fitting parameters are also consistent with those derived when the ASCA and ROSAT data are considered individually. The \( \chi^2 \) contours in \( (N_{H,2}, U_X) \)-space assuming \( N_{H,0} = N_{H,0}^{\text{Gal}} \) are also shown (dashed lines) in Figure 2. Allowing the redshift of the ionized gas to vary during the analysis, we find \( 0.115 \leq z_{\text{abs}} \leq 0.217 \) (at 90% confidence), again consistent with the systemic redshift of the host galaxy and limiting the ionized gas to have a velocity of \( \lesssim (\pm 2 \times 10^4) \) km s\(^{-1} \) with respect to the nucleus. In passing, however, we note that the best-fitting models for this combined analysis do consistently overpredict the number of counts observed by SIS below 0.6 keV (\( R_{0.6} \sim 0.5–0.7 \)). This may simply be due to the residual uncertainties in the calibration of the SIS/XRT instrument at these energies or be an artifact of fitting nonsimultaneous data below 0.6 keV in the SIS. The stars show the corresponding data-to-model ratio (again rebinned for clarity) when this model is extrapolated below 0.6 keV.
data sets with different signal-to-noise ratios from instruments with very different energy resolutions. The strength of any emission component is restricted to be that from a full shell of such material, assuming that it was irradiated by the continuum source with a luminosity $\lesssim 1.5$ times that derived from the observations.

3.2. Results from the Fe K-Shell Band

The analysis presented in $\S$ 3.1 did not take into account the potential presence of features in the 6–9 keV band (in the rest frame of the quasar) due to Fe K-shell transitions. Indeed, the data-to-model residuals shown in Figure 1 do show a deficit in this energy range. This absorption feature appears to be present in all four ASCA detectors, and it can be modeled with an absorption edge of energy $E_{\text{abs}}^z$ (in the rest frame of the quasar) and optical depth $\tau$ [where $\tau \propto (E/E_{\text{abs}}^z)^{-3}$ for energies $E \geq E_{\text{abs}}^z$ and zero elsewhere]. Considering the ASCA data alone and fixing $N_{\text{H},0} = N_{\text{Gal},0}$, the addition of these two parameters results in an improvement of $\Delta \chi^2 = 9.2$, significant at greater than 95% confidence ($F$-statistic = 4.9). We find $\tau = 0.35^{+0.38}_{-0.26}$ and $E_{\text{abs}}^z = 7.25^{+0.42}_{-0.33}$ keV. The confidence contours in the $(E_{\text{abs}}^z, \tau)$-plane are shown in Figure 3a, along with the corresponding edge energies for Fe K-shell absorption. It can be seen that the edge is consistent with Fe $\tau-\text{xix}$ at 90% confidence for $\tau > 0.1$, assuming absorbing material in the rest frame of the quasar. The best-fitting $\tau$ corresponds to an equivalent hydrogen column density of $\sim 10^{19}/A_{\text{Fe}}$ cm$^{-2}$, where $A_{\text{Fe}}$ is the abundance of Fe relative to hydrogen. Thus, if the Fe feature is produced in the same material as is responsible for the O features observed at $\lesssim 1$ keV discussed above ($N_{\text{H},z} \approx 2 \times 10^{22}$ cm$^{-2}$), then we require $A_{\text{Fe}} \sim 5 \times 10^{-4}$, a factor of $\sim 10$ greater than the most recent estimations of the “cosmic” abundance (Anders & Grevesse 1989).

We note that a yet superior fit is obtained if the absorption feature is assumed to be “notch shaped” (a saturated line with vertical sides and $\tau = \infty$ within), yielding $\Delta \chi^2 = 18$ compared with the model with no absorption. The best-fitting notch has an equivalent width of $343^{+31}_{-20}$ eV (equivalent to one rebinned spectral bin) and is centered at an energy $7.76^{+0.16}_{-0.24}$ keV (in the rest frame of the quasar; see Fig. 3b) Assuming this is indeed material in the rest frame of the quasar, such an energy is consistent with resonance scattering by Ni $K\alpha$ (N II xxviii) and Fe $K\beta$ (>Fe xx). Although both families of interactions include transitions with relatively large oscillator strengths (0.7–0.8), both interpretations are problematic. In the former case, the cosmic abundance of Ni is far smaller than that for Fe (A$_{\text{Ni}}$/A$_{\text{Fe}}$ = 0.04), making such an interpretation unlikely as a result of the lack of corresponding features due to Fe at lower energies. In the latter case, resonance scattering by Fe $K\alpha$ will dominate that due to Fe $K\beta$ for ionization states above Fe XVI, again making such an interpretation unlikely as a consequence of the lack such a feature in 6.4–6.9 keV band. An alternative explanation of the notch is that it is due to resonance scattering by Fe $K\alpha$, but that the material is outflowing ($\sim 0.1c$ for Fe XX) with respect to the rest frame of the quasar. However, the instrumental and cosmic backgrounds start to become a noticeable fraction of the observed signal from PG 1114+445 in this observation above $\sim 6$ keV. Given that both the SIS and GIS detectors contain background features in this region (see, e.g., Gendreau 1994; Makishima 1996), we consider the form of the absorption to require confirmation before more detailed interpretations can be made.

Emission features due to Fe K-shell processes are common in low-luminosity AGNs (see, e.g., Nandra & Pounds 1994) and have been claimed in high-luminosity AGNs (e.g., Williams et al. 1992; Nandra et al. 1996). With such a deep Fe absorption in our spectrum, we might expect to observe the associated Kx emission. For the ionization levels suggested by the above fits, including an edge (<Fe xx), the emission line’s energy should be close to 6.4 keV. We have tested for the presence of such a line by

![Figure 3](image-url)

**Figure 3.** –(a) Contours of $\chi^2$ corresponding to the 68% and 90% confidence regions for two interesting parameters ($E_{\text{abs}}^z$ and $\tau$) when an additional absorption edge is added to the ionized-absorber model described in $\S$ 3.1 (dashed lines). The solid line shows the contour corresponding to 90% confidence for five interesting parameters ($\Gamma$, $U_x$, $N_{\text{H},z}$, $E_{\text{abs}}^z$, and $\tau$). As can be seen, such a feature is consistent with a variety of ionization states of iron up to $\sim$ Fe XX. (b) Same as (a), but when the “notch shaped” absorption feature is added to the ionized-absorber model. Such a feature is consistent with resonance scattering by Ni $K\alpha$ (<N II xxviii) and Fe $K\beta$ (>Fe xx) in the rest frame of the quasar or Fe $K\alpha$ in outflowing material (see $\S$ 3.2).
adding a narrow Gaussian line to the model at that energy. Although a significant improvement is not obtained, the equivalent width $W_{\text{K}} = 60^{+230}_{-60}$ eV is consistent with the predictions of photoionization models that assume full coverage of the column density implied by the edge fits. If the emission line is broad, as observed in Seyfert 1 galaxies, then the upper limit to $W_{\text{K}}$ is larger by a factor of $\sim 5$.

4. DISCUSSION AND CONCLUSIONS

In the previous section we showed that both the ASCA and the ROSAT spectra from PG 1114+445 are consistent with a single power law continuum with $\Gamma \approx 1.8$ absorbed by a column density of $\sim 2 \times 10^{22}$ cm$^{-2}$ of photoionized gas, $U_X \approx 0.1$. We suggest that this offers the most plausible explanation of the X-ray spectrum of this source, making it only the fifth quasar (alongside MR 2251−178, 3C 351, 3C 273, and IRAS 13349+2438) in which ionized material has been detected along the line of sight. After correcting for absorption (i.e., setting $N_{\text{H},0} = N_{\text{H},2}$ = 0), the X-ray luminosities$^{10}$ are $L_X \approx 5.7 \times 10^{42}$ and $2.7 \times 10^{44}$ ergs s$^{-1}$ over the 0.1−10 keV and 2−10 keV bands (source frame), respectively. This is comparable to the highest luminosities of photoionized clusters around with column densities in the range $N_{\text{H},z} \approx 10^{21}$−$10^{23}$ cm$^{-2}$. The underlying spectral index also lies in the range found in Seyfert 1 galaxies. The underlying continuum could not be determined unambiguously from the ROSAT PSPC data from the RLQ 3C 351 ($z = 0.371, L_X \approx 3 \times 10^{45}$ ergs s$^{-1}$). However, the fits including absorption by ionized material reported by Fiore et al. (1993) indicate a similar column density $[N_{\text{H},z} \sim (1-4) \times 10^{22}$ cm$^{-2}]$ to that found in PG 1114+445 and Seyfert 1’s, but that the gas is less ionized ($U_X$ on the order of few $10^{-2}$, after conversion of the quoted ionization parameter to that over the 0.1−10 keV band used here).

Nandra et al. (1997b) have recently reported results from ASCA observations of the RQQ MR 2251−178 ($z = 0.068, L_X \approx 2 \times 10^{45}$ ergs s$^{-1}$), obtaining a lower column density $(N_{\text{H},z} \sim 2 \times 10^{21}$ cm$^{-2}$) and $U_X \approx 0.07$. Brandt et al. (1996) have found evidence of absorption by ionized oxygen in ROSAT PSPC data from IRAS 13349+2438 ($z = 0.107, L_X \approx 10^{45}$−$10^{46}$ ergs s$^{-1}$). Unfortunately, the properties of the ionized material could not be well constrained by those data $(N_{\text{H},z}$ on the order of a few times $10^{21}$−$10^{24}$ cm$^{-2}$, $U_X \approx 0.2$−0.5). However, the lack of significant absorption by neutral material in the PSPC data, along with strong evidence of dust at other wave bands, led Brandt et al. to suggest that the dust may be embedded within the ionized material.

A particularly interesting result of our analysis is the detection of an absorption feature within the Fe K-shell band ($\sim 3.2$). The strength of this feature implies either an Fe/O abundance ratio $\sim 10$ times cosmic or a second zone of highly ionized material, perhaps outflowing from the nucleus. The feature is of similar energy and depth as those observed in Seyfert 1 galaxies by Ginga (Nandra & Pounds 1994) and that possibly detected in an ASCA observation of the RLQ 85 0014+81 (Cappi et al. 1997). Future observations, with higher sensitivity and resolution in the 7−9 keV band, are required to confirm these features and better determine their nature.

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\[ f_{250}/f_{2.5} \text{ keV} = 8.1 \times 10^3 \] (corresponding to an optical−to−X-ray energy index $\alpha_{\text{ox}} = 1.5$). Following Netzer (1996), we assume undepleted "cosmic abundances" [with (He, C, N, O, Ne, Mg, Si, S, Fe)/H = (10$^2$, 3.7, 1.1, 8, 1.1, 0.37, 0.35, 0.16, 0.4)/10$^{-4}$]. For comparison, the column densities in the bound−free transitions in O VII and O VIII are $9.6 \times 10^{18}$ and $5.1 \times 10^{20}$ cm$^{-2}$, respectively. In passing we note that, given the cross sections for these transitions ($2.4 \times 10^{-19}$ and $9.9 \times 10^{-20}$ cm$^2$), the predicted optical depth of O VII ($\tau \approx 2.5$) is in good agreement with that obtained in § 3.1 when the data are modeled by a power law plus O VII and O VIII absorption edges. However, the observed optical depth of O VIII ($\tau \approx 1.1$) is a factor of $\sim 2$ greater than that predicted in our full photoionization calculations, primarily as a result of the modeled optical depth of O VIII having to include the additional opacity due to Fe L-shell and Ne K-shell transitions during the fitting process.

The parameters for the ionized gas obtained here for PG 1114+445 are very similar to those found for Seyfert 1 galaxies. G98 find that the ionization parameter typically clusters around $U_X \sim 0.1$ with column densities in the range $N_{\text{H},z} \sim 10^{21}$−$10^{23}$ cm$^{-2}$. The underlying continuum index also lies in the range found in Seyfert 1 galaxies. The underlying continuum could not be determined unambiguously from the ROSAT PSPC data from the RLQ 3C 351 ($z = 0.371, L_X \approx 3 \times 10^{45}$ ergs s$^{-1}$). However, the fits including absorption by ionized material reported by Fiore et al. (1993) indicate a similar column density $[N_{\text{H},z} \sim (1-4) \times 10^{22}$ cm$^{-2}]$ to that found in PG 1114+445 and Seyfert 1’s, but that the gas is less ionized ($U_X$ on the order of few $10^{-2}$, after conversion of the quoted ionization parameter to that over the 0.1−10 keV band used here).

Nandra et al. (1997b) have recently reported results from ASCA observations of the RQQ MR 2251−178 ($z = 0.068, L_X \approx 2 \times 10^{45}$ ergs s$^{-1}$), obtaining a lower column density $(N_{\text{H},z} \sim 2 \times 10^{21}$ cm$^{-2}$) and $U_X \approx 0.07$. Brandt et al. (1996) have found evidence of absorption by ionized oxygen in ROSAT PSPC data from IRAS 13349+2438 ($z = 0.107, L_X \approx 10^{45}$−$10^{46}$ ergs s$^{-1}$). Unfortunately, the properties of the ionized material could not be well constrained by those data $(N_{\text{H},z}$ on the order of a few times $10^{21}$−$10^{24}$ cm$^{-2}$, $U_X \approx 0.2$−0.5). However, the lack of significant absorption by neutral material in the PSPC data, along with strong evidence of dust at other wave bands, led Brandt et al. to suggest that the dust may be embedded within the ionized material.

A particularly interesting result of our analysis is the detection of an absorption feature within the Fe K-shell band ($\sim 3.2$). The strength of this feature implies either an Fe/O abundance ratio $\sim 10$ times cosmic or a second zone of highly ionized material, perhaps outflowing from the nucleus. The feature is of similar energy and depth as those observed in Seyfert 1 galaxies by Ginga (Nandra & Pounds 1994) and that possibly detected in an ASCA observation of the RLQ 85 0014+81 (Cappi et al. 1997). Future observations, with higher sensitivity and resolution in the 7−9 keV band, are required to confirm these features and better determine their nature.

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