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THE DISCOVERY OF AN O VII EMISSION LINE IN THE *ASCA* SPECTRUM OF THE SEYFERT GALAXY NGC 3783

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ABSTRACT

We report the first observation of an O VII 0.57 keV emission line in a Seyfert 1 galaxy. NGC 3783 was observed by *ASCA* twice over a period of 4 days in 1993 December. The source exhibited a ~30% change in intensity between the two observations, with most of the variability taking place as a result of steepening of the continuum $\lesssim 1$ keV. Spectra from both observations show intense absorption features in the 0.5–1.5 keV band, which can be well fitted by an ionized absorber model of solar composition, column density of $10^{22.2}$ cm^{-2} and ionization parameter of ~7–8; the strongest absorption features being due to O VII and O VIII. Two emission features are also seen in the spectra which we identify as O VII 0.57 keV (equivalent width $\simeq 36$ eV) and O VIII 0.65 keV (equivalent width $\simeq 11$ eV). We find these features are at the intensity predicted by the above ionized absorber model when the covering factor is close to unity.

We also show that the 3–6 keV continuum of the source is well fitted by a $\Gamma = 1.3$–1.4 power-law continuum, a narrow neutral iron *K*-shell fluorescence line and a strong iron *K*-shell absorption edge, possibly corresponding to highly ionized iron. The intensity of neither of these *K*-shell features can be explained by the ionized absorber, and thus must be from a separate component.

Subject headings: galaxies: active — galaxies: individual (NGC 3783) — galaxies: nuclei — X-rays: galaxies

1. INTRODUCTION

The Seyfert 1 galaxy, NGC 3783, at a redshift $z = 0.0097$, has been observed using all the major X-ray satellites since its detection in the *Ariel V* sky survey (see Turner et al. 1993, hereafter Paper I, and references within). In Paper I we reported the results from a high signal-to-noise *ROSAT* observation of NGC 3783, along with a reanalysis of archival *Ginga* and *EXOSAT* observations. Strong evidence for deep absorption features in the 0.5–1.5 keV band was reported, which were associated with O VII–VIII absorption due to a column of ionized material (a so-called "warm absorber"). Currently, there are several other active galactic nuclei (AGN) known to contain similar features such as the Seyfert 1 galaxies NGC 4151 (Weaver et al. 1994), MCG-6-30-15 (Nandra & Pounds 1992; Fabian et al. 1994), EXO 055620−3820.2 (Turner et al. 1995), along with the quasar 3C 351 (Fiore et al. 1993). It is anticipated that *ASCA* will find many more examples.

Here we present the results of two *ASCA* observations of NGC 3783 performed in 1993 December. We confirm the presence of the ionized material, and demonstrate that it is consistent with a physically realistic ionized absorber model. We report the first detection of oxygen emission lines that are predicted to originate in the same gas component, and briefly discuss the unusual iron *K*-shell absorption and emission features in this source.

2. OBSERVATIONS AND REDUCTION

The two observations reported here were carried out by *ASCA* on 1993 December 19 and 23. *ASCA* has four instruments covering the 0.4–10 keV X-ray energy band (Tanaka, Inoue, & Holt 1994): two Solid State Imaging Spectrometers (SIS) each consisting of four CCD chips, and two Gas Imaging Spectrometers (GIS). Both the observations reported here were carried out with 2 CCD chips exposed on each SIS, with the target at the nominal pointing position. The data collected in "Faint" and "Bright" modes were combined.

The following data-selection criteria were applied: that the spacecraft was outside of the South Atlantic Anomaly; the elevation angle above the Earth's limb was greater than 5° for GIS data, and greater than 8° for SIS data; the Bright Earth angle (elevation angle above the Sun-illuminated Earth's limb) was >13°; the magnetic cut-off rigidity was less than 7 GeV c^{-1}; and data taken within 100 s of the day/night transition were rejected. "Hot" and "flickering" pixels were removed from the SIS, and a few hundred seconds of data at the start of the observations, when the satellite pointing was not yet stable, were also removed. After these screening criteria had been applied, we extracted a light curve for each instrument, and manually removed time periods of data dropout or spikes due to high background. These selection criteria resulted in effective exposure times of ~38 ks in each instrument, split approximately equally between the two epochs.

Images were extracted from the screened and cleaned data from all instruments, and region descriptors were defined for extracting light curves and spectra. For the two SIS instruments, we used circular extraction cells of ~4 arcmin radius centered on NGC 3783, with the background taken at the edge of the same CCD chip. For the two GIS instruments, we used extraction cells of ~6 arcmin radius centered on NGC 3783, with the background taken in a source-free region of the same GIS.

The most important result reported in this *Letter* is an excess flux detected at ~0.6 keV which we interpret as an O VII emission line (§ 3 below). This feature is present at a similar intensity in spectra obtained using both SIS0 and SIS1 when analyzed separately. However, since the identification of the feature with O VII emission depends on the accurate subtrac-

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tion of background and instrumental features at or around this energy, we have carried out a number of tests to confirm it is intrinsic to NGC 3783. These are discussed below in some detail since they are of general importance for future *ASCA* observations.

From an analysis of several background fields, Gendreau (1994) has shown that at energies $\lesssim 1$ keV the *ASCA* SIS background spectra contain a feature in the 0.4–0.6 keV band in excess of a relatively smooth continuum. This feature is believed to be a combination of an instrumental feature (related to escape peak features from the gold *M*-edge features around 2.2 keV due to the telescopes and CCD housings, and the fluorescence silicon K_α line at 1.74 keV from within the CCDs themselves) and a real feature in the cosmic X-ray background (CXB). Gendreau (1994) reports the former at least a factor ~ 7 smaller than the latter in the background fields. Such a feature is also visible in both our SIS background spectra, at a level consistent with that reported by Gendreau (1994), and a factor $\lesssim 10$ *weaker* than that seen in our background-subtracted spectra of NGC 3783. It would require an extremely unlikely fluctuation of this size in the amplitude of the CXB (between our source and background regions, separated by ~ 7 arcmin) for the observed feature to be accounted for by an under-subtraction of the CXB. Similarly, if the observed feature were due to the escape peaks arising from the silicon and/or gold lines in the detector, then we would have expected to have seen intense excess emission in the 1.5–2.5 keV band. Such emission is not seen.

The manual screening of *ASCA* data is currently somewhat subjective, therefore we also experimented using more conservative screening criteria and background subtraction techniques to further test the reality of the O VII feature. We found that rescreening the data such as to accept only that taken when the Earth elevation angle was more than 10°, and the Bright Earth angle was more than 20° had no effect on either the overall spectrum or the strength of the O VII feature, nor did excluding all data taken during "satellite day." We also found our results to be unaffected by performing background subtraction using simultaneous data taken in the (source-free) offset chip during the observation (utilizing the new technique to convert the offset chip data into equivalent source chip data), or using the "standard" background spectra (see Day et al. 1994). Thus we conclude that the excess feature is indeed intrinsic to NGC 3783 and the following section addresses its intensity and physical nature.

3. RESULTS AND DISCUSSION

3.1. *Temporal Analysis*

All instruments showed NGC 3783 to have varied between the observations, with mean background-subtracted count rates of 1.0–1.3 counts s^{-1} in the 0.4–10 keV band (SIS0) and 0.8–1.0 counts s^{-1} in the 0.8–10 keV band (GIS) for the December 19 and 23 epochs respectively. Slow trends of (decreasing) intensity were also seen within both epochs, with a halving timescale of ~ 20 hr. However, most of the variability seen between the observations is the result of a softening of the spectrum (below ~ 1 keV) between December 19 and December 23. For example, in the 0.5–1.2 keV band (the "XM1" band of Netzer, Turner, & George 1994) the mean (SIS0) count rates increased by a factor 1.5 (from 0.17 and 0.26) between observations, with a peak to trough variability of a factor 2.1 ± 0.2. This softening of the spectrum is demonstrated in Figure 1, which shows the ratio of the two observations as a function of energy. As described below, this spectral variability cannot be explained by change of ionization conditions only, and a real continuum steepening must have taken place below ~ 1 keV.

3.2. *The Hard X-ray Continuum and the Iron K Line*

The source strength and variability behavior described above suggest little spectral variation within either the December 19 or 23 observation (Fig. 1). We therefore restrict our spectral analysis in this section to the mean spectra from each of those two epochs. The total number of source counts in each instrument during each epoch was in the range 1.6–2.3 × 10^4 counts.

A simple power-law fit to the overall *ASCA* spectrum, corrected for Galactic absorption (parameterized by an effective hydrogen column density $N_H = 8.5 \times 10^{20}$ cm^{-2} as found by Alloin et al. 1994, assuming cosmic abundances of Morrison & McCammon 1983) clearly shows a wide absorption trough in the 0.6–1.3 keV band. Such a feature was first reported in NGC 3783 by Turner et al. (1993), and interpreted as absorption by highly ionized gas. Fitting of such a component requires an estimate of the shape of the unabsorbed continuum which, in the case of NGC 3783 is the energy range of 3–10 keV. The following analysis addresses this hard continuum, and the associated line and absorption features.

Fitting only the data between 3–6 keV with a simple power-law (with $N_H = 8.5 \times 10^{20}$ cm^{-2}) gave acceptable fits with $\Gamma = 1.39^{+0.06}_{-0.06}$ (χ^2_ν/d.o.f. = 0.91/709) and $\Gamma = 1.29^{+0.06}_{-0.06}$ (χ^2_ν/d.o.f. = 1.00/709) on December 19 and 23, respectively (errors are quoted at 90% confidence for one interesting parameter, $\chi^2_{min} + 2.706$, throughout). Comparing the 3–10 keV data with such a power-law model suggests the presence of

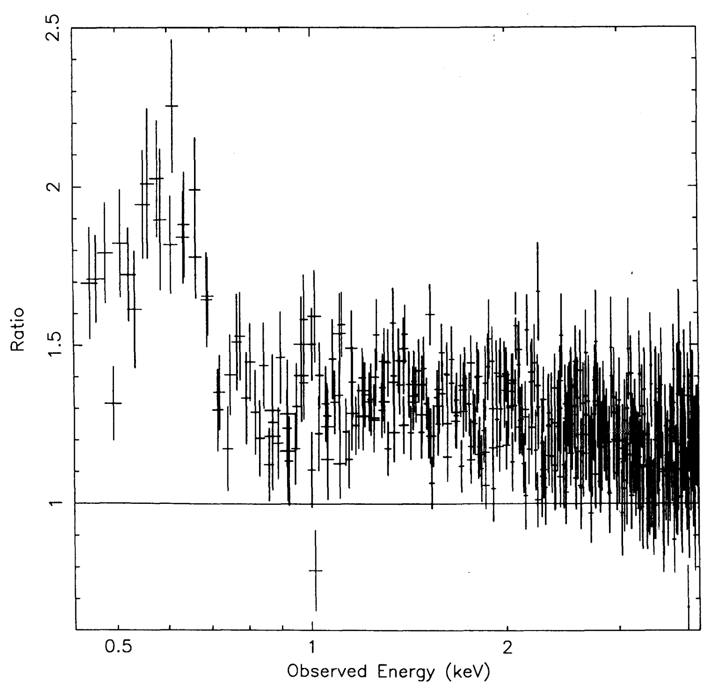

FIG. 1.—Ratio residuals obtained by dividing the December 23 *ASCA* spectrum of NGC 3783 by the best-fitting warm absorber model to the December 19 data. A clear change in both intensity and spectrum is evident, particularly the dramatic steepening toward lower energies.

iron K-shell emission and absorption on December 19, and absorption only on December 23. With the addition of a Gaussian emission line and absorption edge, on December 19 we find the best-fitting line to have a (rest frame) energy $6.36^{+0.05}_{-0.05}$ keV, consistent with K-shell fluorescence from neutral iron. The line shows no evidence of significant broadening (width <150 eV), and has an equivalent width of 105^{+35}_{-31} eV. Whilst an emission line is not significantly detected on December 23, the data are consistent with a narrow line at the same energy and intensity as that observed 4 days earlier, with the drop in equivalent width (to 33^{+20}_{-29} eV) being attributable to the increase in continuum level relative to the line. The absorption edge was found to have best-fitting (rest frame) energies of $7.7^{+0.3}_{-0.2}$ keV and $7.2^{+0.1}_{-0.1}$ keV, and depths $\tau = 0.38^{+0.13}_{-0.11}$ and $\tau = 0.35^{+0.10}_{-0.08}$ on December 19 and 23 respectively. A detailed analysis of the K-shell features in NGC 3783, will be presented elsewhere.

3.3. *Ionized Absorber and Oxygen Emission Lines*

Spectral analysis of the background-subtracted datasets over the 0.45–2.0 keV band was carried out including the partially ionized absorber model of Netzer (1993). The analysis assumes the same density ($n = 10^{10}$ cm^{-3}), composition (solar) and ultraviolet continuum shape as in Netzer (1993; see also Netzer et al. 1994). The continuum shows a "blue bump" in the ultraviolet, like many AGN spectra, joining smoothly to the soft X-ray band at 0.2 keV with a standard $\alpha_{OX} = 1.35$, a hard X-ray slope of $\Gamma = 1.5$, close to our previous analysis, and a sharp cutoff at 50 keV. (As stated in Netzer et al. 1994, the exact value of the spectral index in the X-ray band has little effect on the level of ionization.) As above we fixed the Galactic (neutral) absorption at $N_H = 8.5 \times 10^{20}$ cm^{-2}.

The physical picture we wish to study is of a large number of "clouds" near a central continuum source. The clouds are heated and ionized solely due to photoionization, and obscure part or all of our line of sight to the central source, giving rise to the typical signature of an ionized absorber. As pointed out by Netzer (1993), emission and reflection by the highly ionized material can be important in modifying the shape and the depth of the absorption troughs. Thus we have also investigated a large range of covering factors which affects the intensity of such emission. Two generic models are investigated: (a) Pure absorption by large clouds, whereby the line of sight is completely blocked by an absorber with a small covering factor, giving rise to negligible emission and reflection components; (b) Absorption, emission and reflection from an ensemble of small clouds with a full covering of the central source.

The results from fitting the December 19 dataset with a pure absorption model are shown in Figure 2*a*. The derived model parameters are an ionized column density $N_H^{ion} = 1.69^{+0.08}_{-0.08} \times 10^{22}$ cm^{-2} and ionization parameter $U = 8.5^{+0.5}_{-0.5}$ [$U = Q(H)/4\pi r^2 nc$, where Q(H) is the number of Lyman continuum photons, r the distance from the ionizing source, and c the speed of light]. It can be seen that there is generally very good agreement between the data and model (with χ^2_ν/d.o.f. = 1.14/251), with the strong absorption features well fitted by the O VII and O VIII edges in the model. However, the data show a clear excess in the 0.5–0.65 keV band. This excess is dramatically reduced by the addition of narrow, Gaussian lines at energies of 0.57 and 0.65 keV, with equivalent widths of 45 ± 11 and 18 ± 11 eV, respectively. We identify those additional lines as due to the primary transitions of helium-like oxygen blend (568.7–574.0 eV) and as the Lyα line of O VIII (at 654 eV).

We further test this idea by fitting the spectrum with model (b), containing absorption, emission, and reflection features. We find values of $N_H^{ion} = 1.52^{+0.07}_{-0.07} \times 10^{22}$ cm^{-2} and ionization parameter $U = 7.4^{+0.4}_{-0.5}$, with $\Delta\chi^2 = 29$ (a significant improvement, greater than 99% confidence). The small change in U between this fit and that found for model (a) is due to warm absorber features in other parts of the soft X-ray spectrum. As can be seen from Figure 2*b*, the overall agreement is excellent and the previous excess emission almost disappears. From the theoretical model spectrum shown in Figure 2*c* it can be seen that the O VII and O VIII lines are indeed the most prominent features in the emission spectrum, but note also that some bound-free continua are also important just beyond the absorption edges. The calculated line equivalent widths of this model are 36 eV for O VII 0.57 keV and 11 eV for O VIII 0.65 keV, in very good agreement with the previous, arbitrarily modelled lines.

We note that the values obtained here for the N_H^{ion} and U differ somewhat from those obtained in Paper I. The Yaqoob & Warwick (1991) model used in Paper I is based on a "modified CLOUDY" calculation in which an optically thick cloud is approximated by many optically thin layers and emis-

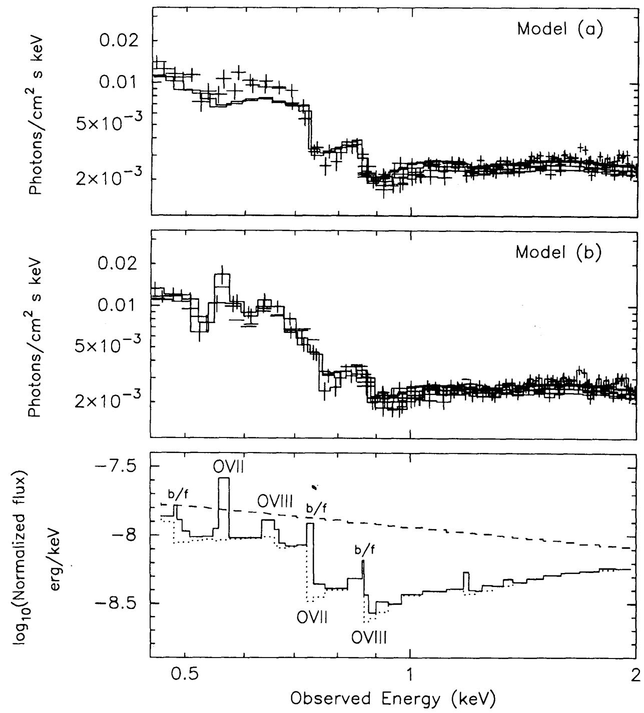

FIG. 2.—Soft X-ray spectra from the *ASCA* observation of NGC 3783 carried out on 1993 December 19. *Upper panel*: the data and (*solid line*) unfolded, best-fitting warm absorber model in which absorption processes only are taken into account [model (a), see text]. An excess of emission is evident in the 0.5–0.7 keV band, which we interpret as arising primarily due to a blend of O VII emission lines in the range 568–574 eV and an O VIII emission line at 654 eV. *Middle panel*: as above, but for the best-fitting warm absorber model containing absorption, emission and reflection [model (b), see text]. It can be seen that such a model is in excellent agreement with the data, and the 0.5–0.7 keV excess disappears. *Lower panel*: the calculated spectrum of NGC 3783 for (*dotted*) the absorption-only case, and (*solid*) the absorption, emission and reflection case. The dashed line shows the underlying, unabsorbed continuum. The strongest O VII and O VIII emission lines are marked. Also note the sharp bound-free emission (marked "b/f") adjacent to the absorption edges.

sion features are not included. The models used here were calculated in a fully self-consistent manner using the numerical code ION (Netzer 1993) and includes all the important physical processes, and we feel is physically more realistic. There are also slight differences between the UV spectrum assumed by the two models, and of course the *ASCA* spectra presented here have a far higher spectral resolution than the PSPC spectra presented in Paper I.

We conclude that the presence of emission in the model considerably improves the quality of the fit and that the observed O VII and O VIII emission lines are very close to the intensity predicted by warm absorber models in which the ionized material has a high covering factor. The O VII blend is the most prominent since it is stronger, closer in energy to the peak in the excess seen in Figure 2*a*, and is observed against a relatively flat continuum (Fig. 2*c*). The formal detection of the O VIII line is marginal in these datasets, due to its weakness and close proximity to an absorption edge (a somewhat different amount of absorption, combined with a somewhat differing underlying continuum shape, can cause an impression of a line at this, moderate *ASCA* resolution range). We note that some Fe *K*-shell emission is expected from the ionized material, but at an intensity only able to explain a tenth of that observed (§ 3.2).

The emission and absorption features are also clearly present in the December 23 observation of NGC 3783, with general characteristics similar to those described above. The source was brighter at the time of this later observation, and has a softer underlying continuum $\lesssim 1$ keV. The December 23 data are also consistent with a warm absorber model. However a detailed discussion of the corresponding changes in the ionized material and their implications is beyond the scope of this *Letter*, which stresses the discovery of the line.

We predict that O VII and O VIII emission lines will be found in the spectra of other AGN by future *ASCA* observations. Indeed the same emission feature appears to be present in the MCG-6-30-15 spectrum published by Fabian et al. (1994). The lines are predicted to be stronger in objects with larger ionized column and larger covering factor and are more noticeable in objects of strong absorption, due to the suppression of the local continuum. The location of the ionized medium is currently unclear, but it is possible that it is inside the broad line region. In NGC 3783, this is less than about 2–5 light-days, as recently confirmed by line reverberation studies (Reichert et al. 1994), and perhaps as close as 1 light-day to the central source. In such a case, large continuum fluctuation will introduce changes in line intensity that could be detected by careful monitoring of the object. This is the best, perhaps the only, way to find the location of warm absorbers in AGNs.

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REFERENCES

Allion, D., et al. 1994, A&A, in press
Day, C. S. R., et al. 1994, The ABC Guide to ASCA Data Reduction, NASA/GSFC
Fabian, A. C., et al. 1994, PASJ, 46, L59
Fiore, F., Elvis, M., Mathur, S., Wilkes, B., & McDowell, J. C. 1993, ApJ, 415, 129
Gendreau, K. 1994, *ASCA* News, 2, 5
Morrison, R., & McCammon, D. 1983, ApJ, 270, 119
Nandra, K., & Pounds, K. A. 1992, Nature, 359, 215
Netzer, H. 1993, ApJ, 411, 594
Netzer, H., Turner, T. J., & George, I. M. 1994, ApJ, 435, 106
Reichert, G. A., et al. 1994, ApJ, 425, 582
Tanaka, Y., Inoue, H., & Holt, S. S. 1994, PASJ, 46, L37
Turner, T. J., Nandra, K., George, I. M., Fabian, A. C., & Pounds, K. A. 1993, ApJ, 423, 621 (Paper I)
Turner, T. J., George, I. M., & Madejski, G. M. 1995, in preparation
Weaver, K. A., et al. 1994, ApJ, 423, 621
Yaqoob, T., & Warwick, R. S. 1991, MNRAS, 248, 773