O AND Ne K ABSORPTION EDGE STRUCTURES AND INTERSTELLAR ABUNDANCE TOWARD CYGNUS X-2

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ABSTRACT

We have studied the O and Ne absorption features in the X-ray spectrum of Cyg X-2, observed with the Chandra LETG. The O absorption edge is represented by the sum of three absorption edge components within the limit of the energy resolution and the photon counting statistics. Two of them are due to the atomic O; their energies correspond to two distinct spin states of photoionized O atoms. The remaining edge component is considered to represent compound forms of oxide dust grains. Since Cyg X-2 is about 1.4 kpc above the Galactic disk, the H column densities can be determined by radio (21 cm and CO emission line) and Hα observations, with relatively small uncertainties. Thus, the O abundance relative to H can be determined from the absorption edges. We found that the dust scattering can affect the apparent depth of the edge of the compound forms. We determined the amplitude of the effect, which we consider to be the largest possible correction factor. The ratio of column densities of O in atomic to compound forms and the total abundance of O were determined to be in the ranges 1.7±3.0 to 2.8±5.1 (ratio) and 0.63±0.12 to 0.74±0.14 solar (abundance), taking into account the uncertainties in the dust-scattering correction and in the ionized H column density. We also determined the Ne abundance from the absorption edge to be 0.75±0.20 solar. These abundance values are smaller than the widely used solar values, but consistent with the latest estimates of solar abundance.

Subject headings: dust, extinction — ISM: abundances — X-rays: binaries — X-rays: individual (Cygnus X-2) — X-rays: ISM

1. INTRODUCTION

The metal abundance in the interstellar medium (ISM) is an important parameter for the understanding of the chemical evolution of the universe. However, large uncertainties remain in our knowledge of this abundance. The solar abundance is sometimes regarded as the average in our Galaxy. However, UV absorption lines due to interstellar gas and optical absorption lines in the atmosphere of young B stars have indicated that the metal abundance in the ISM of our Galaxy is on average about two-thirds of the solar abundance (Savage & Sembach 1996; Snow & Witt 1996). However, both methods contain uncertainties, because the former method is only sensitive to matter in atomic forms, while the abundance of B star atmospheres might be different from that of ISM. Indeed, Sofia & Meyer (2001) recently claimed that B star abundances are lower than the ISM abundance and that the solar abundance is close to the ISM abundance. Moreover, the solar abundance itself is not determined well. Recent values by Grevesse & Sauval (1998) and Holweger (2001) are significantly lower than the values in the widely used table of Anders & Grevesse (1989).

High-resolution X-ray spectroscopy of absorption features due to the interstellar matter is a powerful tool to measure the amount of interstellar metal. It is sensitive to both the atomic (gas) and compound (molecular and dust grain) forms and can distinguish them by the chemical shifts. There are absorption lines and edges of many elements in the X-ray energy range. We can determine the column densities of these elements in different forms separately, integrating toward the X-ray source. However, the observation requires both high energy resolution and good statistics. Schattenburg & Canizares (1986) determined the O column density toward the Crab Nebula with the Focal Plane Crystal Spectrometer (FPCS) on the Einstein Observatory. They could not separate atomic and compound forms. Also, they were not able to determine the O abundance, since the H column density toward the Crab Nebula was not known. Paerels et al. (2001) analyzed the O and Ne absorption structures of the X-ray binary X0614+091, observed with the low-energy transmission grating (LETG) on the Chandra X-Ray Observatory. They successfully separated the absorption features of O in atomic and compound forms. They also determined the abundance ratio of Ne to O. However, they could not determine the O abundance, because the H column density toward the source is not known. Schulz et al. (2002) determined the column densities of O, Ne, Mg, Si, and Fe toward Cyg X-1 with Chandra high-energy transmission grating (HETG) data. They discussed the abundances of O, Ne, and Fe. However, it was necessary to assume the abundances of all other elements to be solar, in order to estimate the H column density toward Cyg X-1 from the X-ray spectrum.

In this paper, we analyze the spectrum of Cyg X-2 obtained with the Chandra LETG and HRC-I. Cyg X-2 is a low-mass X-ray binary (LMXB) located at (l, b) = (87°33′, −11°32′), and its distance is determined to be 7.2 kpc from the optical counterpart and X-ray burst with mass ejection.
(Cowley, Crampton, & Hutchings 1979; Smale 1998; Orosz & Kuulkers 1999). Smale (1998) claimed a distance of 11.6 kpc; however, this is because he assumed the Eddington luminosity for a hydrogen-rich atmosphere. If we assume a helium-rich atmosphere, which is more realistic for type I bursts (Lewin, van Paradijs, & Taam 1995), the distance is consistent with 7.2 kpc. Given this distance, Cyg X-2 is located ~1.4 kpc above the Galactic disk. Thus, the H column density toward Cyg X-2 can be estimated from 21 cm (H i), CO (H2), and Hα (H ii) observations, with relatively small errors. Because of the featureless X-ray spectrum of the LMXB, the high brightness, and the well-determined H column density to the source, Cyg X-2 is one of the best X-ray sources for the study of the interstellar abundance with X-ray absorption.

First, we discuss the H column density toward Cyg X-2 (§ 2). Then we show the observational results (§ 3) and discuss the O and Ne abundances and the uncertainties of the present results (§ 4). Throughout this paper, we quote single parameter errors at the 90% confidence level, unless otherwise specified.

2. H COLUMN DENSITY TOWARD CYG X-2

Interstellar hydrogen is distributed in three different forms: atomic (H i), molecular (H2), and ionized (H II).

The column density of atomic hydrogen is measured by the 21 cm radio emission. In the H i map of Dickey & Lockman (1990), the H column density (NH) is given at grid points of 0 8 separation. By interpolating between the values of nearby points, the column density in the direction of Cyg X-2 is estimated to be NH = 2.17 × 1021 cm−2. Since the scale height of atomic hydrogen is ~140 pc, the total column density of our Galaxy can be regarded as the column density to Cyg X-2. The standard deviation of the NH-values within 2 R of Cyg X-2 is 0.1 × 1021 cm−2. The power spectra of the small-scale spatial fluctuation of the Galactic NH, were measured for different directions (Crovisier & Dickey 1983; Dickey et al. 2001). On spatial scales less than 1 R, the power-law index of the power spectra is in the range from ~3 to ~4. Assuming the same shape of the power spectrum for the spatial fluctuations in the vicinity of Cyg X-2, we estimate the rms amplitude of the spatial fluctuation less than 2 R to be 0.12 × 1021 cm−2 and regard this as the 1 σ error of the estimation.

Koch-Miramond & Naylor (1995) determined the upper limit of molecular hydrogen column density toward Cyg X-2, from the upper limit of the CO emission line in the direction of Cyg X-2, to be 0.05 × 1021 cm−2 (90% significance level). According to them, the contribution of H2 in NH is smaller than 0.10 × 1021 cm−2.

The total neutral H column density (NH + 2NH2) is thus estimated to be 2.17 ± 0.20 × 1021 cm−2. On the other hand, the reddening toward Cyg X-2 is determined to be E(B−V) ≈ 0.4 (McC1nt0ck et al. 1984). Combining this with the relation NH + 2NH2 = 5.8 × 1021E(B−V) atoms cm−2 mag−1 (Bohlin, Savage, & Drake 1978), we obtain NH + 2NH2 ≈ 2.3 × 1021 cm−2, which is consistent with the above estimate.

A large fraction (~97%; Mathis 2000) of ionized H atoms exists in the warm ionized interstellar medium (WIM) of temperature T ~ 8000 K, distributed in our Galaxy with a scale height h of ~900 pc and a volume filling factor f of ≥0.2. In the WIM, oxygen is effectively ionized through the charge exchange process. The number densities of neutral/ ionized oxygen and hydrogen are related by N(O i)/N(H i) = (8/9)N(H2)/N(H i) (Field & Steigman 1971).

According to more recent model calculations by Sembach et al. (2000), the ionization fraction of Ne is also similar to that of H; in their composite model, the values of log [N(X′)/N(Xtotal)], where X = H, O, or Ne and i represents the ionization states, are, respectively, ~0.73 and ~0.09 for H i and H II, ~0.71 and ~0.09 for O i and O II, and ~0.70 and ~0.10 for Ne I and Ne II. Therefore, N(Xtotal)/N(Xtotal) = N(H i)/N(H II) is a good approximation for gas-phase O and Ne, and we do not need to consider ionized H when we calculate atomic O and Ne abundances.

On the other hand, since interstellar dust grains are thought to coexist with the WIM, we need to take into account the column density of ionized H when we estimate the abundance of O in compound forms. We estimated it from the Hα emission line intensity in the direction of Cyg X-2, obtained from the Wisconsin Hα Mapper (WHAM) survey.1 The intensity is 14.6 ± 3.8 R. From the line intensity, the total emission measure in the column toward Cyg X-2 is estimated to be (1.28 ± 0.33) × 1020 (T/8000 K) cm−5, where we applied an extinction correction factor of 1.3, assuming Rv = 3.1 (Mathis 1990). Assuming the spatial distribution described above, the emission measure and the column density are, respectively, related to the local ionized H density in the Galactic plane, nh0, by

\[ EM = f n_0^2 \int_0^\infty \exp \left(-\frac{x \sin b}{h}\right) \, dx \]

and

\[ N_{H^+} = f n_0 \int_0^d \exp \left(-\frac{x \sin b}{h}\right) \, dx \]

where d and b are the distance and the Galactic latitude of Cyg X-2, respectively. From these we obtain N(H II) = 0.70 ± 0.18 × 1021(f/0.2)1/2 cm−2. As a nominal value, we adopted N(H II) = 0.70 ± 0.18 × 1021 cm−2 (f = 0.2; Mathis 2000) and thus N(H total) = 2.87 ± 0.25 × 1021 cm−2. Even for f = 1, N(H II) does not exceed (1.57 ± 0.40) × 1021 cm−2. In Table 1, we summarize the H column densities estimated in this section.

1 See http://www.astro.wisc.edu/wham.
3. ANALYSIS AND RESULTS

3.1. Data Reduction

Cyg X-2 was observed with the LETG/HRC-I for 30 ks on 2000 April 24 (Observation ID 87). We retrieved the archival data from the CXC (Chandra X-Ray Center). Cyg X-2 is known to show both intensity and spectral variations. However, since the X-ray flux varied only ~20% during the observation and since we are interested only in the interstellar absorption features, we integrated all the data after the standard data screening.

Since the spectrum in the archival data we retrieved is known to contain some processing errors,2 we reprocessed the data according to the standard methods described in threads in CIAO 2.2.1 (CALDB 2.10). We first obtained the spectra of the positive and negative orders. Then we summed them, rebinned to 0.025 Å bins, and subtracted the background. The background was only ~2% of the source counts in the wavelength region we used in the later analysis.

HRC-I has almost no energy resolution. The spectrum we obtained contains photons not only of the first-order dispersion but also of the higher orders. We subtracted the higher order spectra, utilizing the method described in Paerels et al. (2001). The mth-order spectrum of photons with a wavelength of λ appears in the wavelength bin λ = mλ0 of the first-order spectrum. Since the LETG/HRC-I system has no detection efficiency below the wavelength λ0, where λ0 = 1 Å, we can neglect the contribution of the mth-order spectrum in the wavelength range λ < mλ0. From the spectrum in the range λ0 < λ < 2λ0 and the efficiency ratio of the second- to the first-order spectra, we can estimate the second-order spectrum in the range 2λ0 < λ < 4λ0 and subtract it from the total spectrum to obtain the first-order spectrum in λ0 < λ < 3λ0. In the same manner, we can subtract higher order spectra from all the wavelength range. We calculated the efficiency ratio from the effective areas of the LETG/HRC-S system provided at the CALDB Web site,3 because the higher order efficiencies are not available for the LETG/HRC-I system and because the efficiency ratios are not dependent on the detector. The calibration files we used are updated compared to those used by Paerels et al. (2001). We show in Figure 1 the spectra with and without higher orders.

We estimated the statistical errors of the first-order spectrum obtained with the above method, considering the error propagations. Because of the error propagations, the statistics of the spectral bins are no longer completely independent. However, the increase of the statistical errors after the higher order subtraction is smaller than 3% in the wavelength ranges we use in the following analysis. We thus treat them to be independent in the spectral fittings.

According to the LETGS calibration report at the CXC,4 the wavelength calibration of LETGS spectra is accurate to 0.02%. This is smaller by an order of magnitude than the statistical errors in the wavelengths determined in the following analyses.

3.2. O Absorption Structure and the Optical Depth

In the observed spectrum of Cyg X-2, we clearly found two absorption lines and an absorption edge near λ ~ 23 Å, besides the instrumental O absorption line and edge (see Fig. 2). The centroid energies of the two absorption lines were determined to be 23.505 ± 0.007 and 23.360 ± 0.014 Å, and thus they were identified with the 1s–2p resonant lines of the atomic and compound O, respectively. However, since the absorption lines are saturated (τ ≈ 1), the absorption column densities cannot be determined accurately from the absorption lines. We thus focus on the absorption edge.

The absorption edge structure was extended compared to the instrumental O K edge, which suggests that the edge structure consists of absorption edge components with different edge energies. A complicated structure is expected for the absorption edge of atomic O, first because photoionized O atoms take two distinct final states with different total spin numbers, and second because there are many absorption lines that cannot be resolved with the LETGS near the absorption edges (McLaughlin & Kirby 1998). The theoretical values of edge energies calibrated with ground experiments are 544.03 eV (22.790 Å, spin 3/2) and 548.85 eV (22.590 Å, spin 1/2) (McLaughlin & Kirby 1998). On the other hand, the edge energy of the compound O depends on the chemical state. Thus, the absorption edge of the compound forms can have an extended structure. The edge energy must be lower than the edge energy of atomic O, but higher than the absorption-line energy. According to Sevier (1979), the edge energy of O in metal oxide is 532.0 ± 0.4 eV (23.31 ± 0.02 Å).

All the O edge structures might not be identified, because the statistics and the energy resolution of the present data are limited. Thus, we first apply a rather simple model to the observed spectrum, then later try more and more complicated models.
We restricted the wavelength range of model fits in order to avoid the contributions of absorption edges of other elements. We did all the analysis described below with several different wavelength ranges. We found that the O absorption optical depth determined from the analysis is not dependent on the wavelength ranges of the fits, so long as the lower and upper limits of the range are within the ranges 17.5–19.0 and 27.0–29.0 Å, respectively. Thus, we show here the results with the fitting range of 18.5–28.0 Å.

We assumed a power-law function for the continuum spectrum. We also included the absorption by neutral matter represented by the $tbabs$ model in the SHERPA program (Wilms, Allen, & McCray 2000), with the O abundance fixed to 0. We included an O absorption edge with a separate absorption edge component represented by the $edge$ model in the SHERPA program. We fixed the H column density of the $tbabs$ absorption model to $2.17 \times 10^{21}$ cm$^{-2}$ and fixed the helium abundance to the solar value. We performed the fits with the abundances of other atoms fixed at several different values between 0.5 and 1.5 solar. We found that the dependence of the best-fit O absorption optical depths on the abundance of other elements is only about 10% of the statistical errors. Thus, we only show the results with the abundance of other elements fixed at the solar values.

Fig. 2.—Spectral fit in the wavelength range including the O absorption structures. The whole wavelength range used in the spectral fits is shown in the bottom panel, while in the top panel the narrow wavelength range containing O edges and absorption lines is expanded. In the top panel and the upper plot of the bottom panel, the observed first-order spectrum is shown as data points with vertical bars that represent 1σ statistical errors. The best-fit model function of the three-edge-component model (the last column of Table 2), convolved with the telescope and the detector response functions, is shown with a thick line. The model function without O edges and absorption lines is shown with a thin line, in order to show the instrumental O absorption structure. Two absorption lines and an extended O edge clearly exist. In the lower plot of the bottom panel, the residuals of the fit are shown.
In the first model, we included two oxygen edge components. We treated the edge energies and the optical depths of the two "edge" components as free parameters. We represented the two O absorption lines with negative Gaussian functions. We fixed the centroid wavelengths to 23.505 and 23.360 Å and the widths to 0.04 Å. The free parameters of the fits were the two O edge energies and optical depths, the normalization factor and the power-law index of the continuum, and the normalization factors of the two Gaussian components. We treated the edge energies and the optical depths of all the edges to vary. In the second and third data columns of Table 2, the results are summarized. The statistical errors are not estimated because the edge energies are strongly coupled.

We show the results of the fits in the first data column of Table 2. The best-fit energies of the two edges were 22.76 ± 0.04 Å and 23.11 ± 0.00 Å, respectively. The former is consistent with the atomic O edge of the spin 3/2 final state within the statistical error. On the other hand, the latter is in the middle of the atomic and the instrumental O absorption edges. Thus, it is likely to represent an O edge of compound forms.

Next, in order to investigate possible complex structures of the edges and the model dependence of the absorption optical depths, we increased the number of edge components one by one. In the fits, we allowed both the energies and optical depths of all the edges to vary. In the second and third data columns of Table 2, the results are summarized. The χ²-value shows a significant improvement from the two- to the three-edge models (99.6% confidence with an F-test). The edge energy of the third edge is 22.58 Å = 549.1 eV. This energy is close to the edge energy for a final spin of 1/2. In the raw spectrum (Fig. 2), we can find this edge structure. On the other hand, the χ²-value did not improve from the three-edge to the four-edge models. Thus, we conclude that the observed O edge structure can be represented with the three-edge model within the limit of the present statistics and the energy resolution; two of the edges represent absorption by atomic O, corresponding to the two different O ion spin states, and the remaining one represents absorption by O in compound forms.

Finally, in order to determine the spectral parameters and their statistical errors for the three-edge model more precisely, we performed the spectral fit for the three-edge model with the two edge energies of the atomic O fixed at the theoretical values. In the last column of Table 2, we show the
results. We estimated the statistical error for the total optical depth for the atomic O edge from the $\chi^2$ contour map, to find the total optical depth of 0.43 ± 0.14. The optical depth of compound forms is 0.26 ± 0.11.

To estimate the column density of O from the absorption optical depth, we adopted the absorption cross section of Verner & Yakovlev (1995): $\sigma_{\text{abs}} = 4.98 \times 10^{-19}$ cm$^2$ for both atomic and compound forms. We obtained $N_{\text{O, atom}} = (8.6 \pm 2.8) \times 10^{17}$ cm$^{-2}$ and $N_{\text{O, comp}} = (5.2 \pm 2.2) \times 10^{17}$ cm$^{-2}$.

Assuming the $N_{\text{H}}$-values of $2.17^{+0.22}_{-0.20} \times 10^{21}$ cm$^{-2}$ for atomic O and $2.87^{+0.25}_{-0.23} \times 10^{21}$ cm$^{-2}$ for compound forms, we estimate the abundance of O to be 0.47 ± 0.16 solar (atomic), 0.21 ± 0.09 solar (compound), and 0.68 ± 0.13 solar (total), where we assumed a solar O abundance of 8.51 × 10$^{-4}$ (Anders & Grevesse 1989). The error of the total abundance was estimated from the $\chi^2$ contour map of the spectral fit, taking into account the difference in $N_{\text{H}}$-values for gas and compound forms and their systematic errors.

### 3.3. Absorption Structure of Ne

In the observed spectrum of Cyg X-2, we also clearly found an absorption edge at 14.3 Å, which is identified with the Ne K edge (Fig. 3). We performed spectral fits to the wavelength range of 12.0–15.5 Å. In addition to the edge, there is an absorption line at 14.6 Å. Because the line wavelength is close to the edge, we included an absorption line in the model function. We employed a model function similar to that used for the O features. We represented the Ne edge with a single-edge model.

In Table 3, we show the results of the fit. The absorption-edge wavelength was consistent with that of the neutral Ne (14.25 Å; Verner & Yakovlev 1995). From the optical depth determined from the fit and the theoretical absorption cross section of Ne i (Verner & Yakovlev 1995), we determined the column density and abundance of Ne i to be (2.00 ± 0.51) × 10$^{17}$ cm$^{-2}$ and 0.75 ± 0.20 times the solar abundance of Anders & Grevesse (1989).

Although the absorption-line energy, 14.599 ± 0.012 Å, is close to the resonant line energy of Ne ii (14.631 Å; Behar & Netzer 2002), it is outside the 90% statistical error domain. Thus, we cannot unequivocally identify this absorption line. However, if we assume that it is Ne ii, the column density estimated from the line is (8.0 ± 2.4) × 10$^{16}$ cm$^{-2}$, which is about 1/4 that of Ne i. Thus, if the absorption line is due to Ne ii, Ne ii can be attributed to the WIM.

### 4. DISCUSSION

We have analyzed the O and Ne absorption structures in the X-ray spectrum of Cyg X-2 observed with the Chandra LETG/HRC-I. The O edge is represented by the sum of three edge components within the limit of present statistics and energy resolution. Two edge components represent absorptions by atomic O; their edge energies are consistent with the theoretical values corresponding to the two distinct final O states of different spin numbers. The edge energy of the remaining edge is lower than that of the other two and is likely to represent O in compound forms. From the depth of the edges, we estimated the O column densities with atomic and compound forms separately.

We tried a four-edge component model in the spectral fits. We find that the sum of the optical depths of all the edge components does not change significantly from three- to four-edge models. Thus, we conclude that the total O column density does not depend significantly on the number of edge components assumed in the spectral models. We estimated the atomic, compound, and total O abundances to be 0.47 ± 0.16, 0.21 ± 0.09, and 0.68 ± 0.13 times the solar abundance of Anders & Grevesse (1989), respectively. The Ne edge is represented with a single-edge model, and the Ne abundance is estimated to be 0.75 ± 0.20 solar. In the errors of abundance quoted above, we included the statistical errors of the spectral fits and the systematic errors of $N_{\text{H}}$ estimated from the spatial fluctuation of 21 cm and Hα emissions and the upper limit of CO emission.

#### Table 3: Results of Spectral Fits of Ne K Edge

| Parameter                                  | Best-fit Value |
|--------------------------------------------|----------------|
| $\chi^2$/dof                                | 149.724/133    |
| Power Law                                  |                |
| Normalization (photons s$^{-1}$ keV$^{-1}$ cm$^{-2}$ at 1 keV) | 1.685 ± 0.023  |
| Photon index                               | 1.328$^{+0.070}_{-0.022}$ |
| Absorption Line                            |                |
| Centroid (eV)                              | 849.24 ± 0.68  |
| Centroid (Å)                               | (14.559 ± 0.012) |
| Equivalent width (eV)                      | 0.541 ± 0.160  |
| Optical depth                              | 0.059 ± 0.015  |

![Fig. 3.—Spectral fit in the wavelength range including the Ne absorption structures. Top: Observed first-order spectrum with 1σ error bars and the best-fit model function, convolved with telescope and detector response functions. Bottom: Residuals of the fit.](image-url)
There is an additional systematic error in the abundance of O in compound forms, arising from the uncertainty in the spatial distribution of the WIM. If we consider the extreme case in which its volume filling factor is 1, the O abundance reduces to $0.16 \pm 0.07$ (compound form) and $0.63 \pm 0.12$ (total).

It is very unlikely that the O and Ne absorption edges are associated with the circumstellar matter in the Cyg X-2 binary system. Suppose that the absorption column of $N_H \sim 2 \times 10^{21}$ cm$^{-2}$ is located at a distance $r$ from the X-ray source. The ionization parameter, $\xi = L_X/\langle n r^2 \rangle$, must be smaller than $\sim 10$, so that O is neutral (Kallman & McCray 1982). With $L_X = 10^{38}$ ergs s$^{-1}$, we find $r \gtrsim 10^{16}$ cm. This is much larger than the size of the binary system ($\sim 10^{12}$ cm; Cowley et al. 1979). This is consistent with the facts that all emission- and absorption-line features found in LMXBs are from highly ionized atoms (see, e.g., Asai et al. 2000; Cottam et al. 2001) and that low-ionization emission lines from the Cyg X-2 system are from near the companion star (Cowley et al. 1979).

About $\frac{1}{2}$ of the O contributing to the absorption edges is in compound form. Dust grains are considered to contribute to this component. In such a situation, the optical depth for dust scattering of X-rays is not negligible compared to the absorption, if we assume a typical dust radius of $0.1 \mu$m. Scattered X-rays form an extended halo on the few-arcminute scale (Hayakawa 1970; Mauche & Gorenstein 1986; Predehl & Schmitt 1995). Since the scattering cross section is dependent on the X-ray energy, the energy spectrum of the scattering halo is modified by scattering. However, if multiple scattering is negligible and if the spatial distribution of dust is uniform over the spatial scale corresponding to the dust halo, the energy spectrum of total photons, i.e., the sum of the unscattered core and the scattered halo, is not modified by dust scattering. This is not the case for the present energy spectrum obtained with the LETG, since we derived the energy spectrum only from the central $1''$ of the X-ray image. Because the scattering cross sections show anomalous features around absorption edges (Mitsuda et al. 1990), the dust scattering will affect the estimate of the absorption column density; the scattering cross section is smaller at the energy just above the edge (at the wavelength shorter than the edge), while the absorption cross section is larger. This leads to an underestimate of the O absorption column density. We estimated the amplitude of this effect in the following way.

The total scattering cross section of an X-ray photon of a wavelength $\lambda$ with a dust grain of a radius $a$ is given by

$$\sigma_{\text{dust, sc}} = 2\pi a^2 \left( \frac{2\pi a}{\lambda} \right)^2 \left( \frac{N_{\ell} \lambda^2}{2\pi} \right) \left( f_1 + if_2 \right)^2,$$

under the Rayleigh-Gans approximation (van de Hulst 1957), where $N$ is the number of atoms per unit volume, $r_0$ is the classical electron radius, and $f_1$ and $f_2$ are the atomic scattering factors (Henke, Gullikson, & Davis 1993). The Rayleigh-Gans approximation is valid for $(2\pi a/\lambda)(N_{\ell} \lambda^2/(2\pi)(f_1 + if_2)) \ll 1$.

Because the factor $|f_1 + if_2|$ becomes small near the absorption edge, the dust-scattering cross section is reduced at the edge. Assuming typical chemical compositions and densities of dust grains (FeSiO$_4$, FeSiO$_3$, Mg$_2$SiO$_4$, and MgSiO$_3$), we estimate the reduction of the scattering cross section at the O edge to be in the range

$$\Delta \sigma_{\text{dust, sc}} = (0.53-0.93) \times 10^{-10} \left( \frac{a}{0.1 \mu m} \right)^4 \text{cm}^2.$$

Assuming the number density of dust to be proportional to $a^{-3.5}$, with a cutoff at $a_{\text{max}}$ (Mathis, Rumpl, & Nordsieck 1977), we calculate the reduction of the scattering cross section per O atom,

$$\Delta \sigma_{\text{sc}} = (0.74-1.44) \times 10^{-19} \left( \frac{a_{\text{max}}}{0.1 \mu m} \right) \text{cm}^2.$$

Thus, the reduction of the scattering cross section can be a few tens of percent of the absorption cross section, $\sigma_{\text{abs}} = 4.98 \times 10^{-19}$ cm$^2$. The maximum grain radius contributing to X-ray scattering has been estimated from the spatial size of dust-scattering halos. Mauche & Gorenstein (1986) and Mitsuda et al. (1990) suggested $a_{\text{max}} = 0.05-0.1 \mu$m, but recently, Witt, Smith, & Dwek (2001) suggested the presence of grains with radii as large as $0.5 \mu$m. Adopting $a_{\text{max}} = 0.1 \mu$m and assuming that O in compound forms are all in dust grains, the column density of O in compound forms increases from $5.2 \times 10^{17}$ cm$^{-2}$ to $(6.1-7.3) \times 10^{17}$ cm$^{-2}$. At the O edge energy, the Rayleigh-Gans approximation is valid for $(2\pi a/\lambda)(N_{\ell} \lambda^2/(2\pi)(f_1 + if_2)) \ll 1$.

### Table 4

| Atom | Form | Case 1$^a$ | Case 2$^b$ | Case 3$^c$ | Case 4$^d$ |
|------|------|-----------|-----------|-----------|-----------|
| O... | Gas phase$^a$ | $0.47 \pm 0.16$ | $0.47 \pm 0.16$ | $0.47 \pm 0.16$ | $0.47 \pm 0.16$ |
|      | Compound | $0.21 \pm 0.09$ | $0.16 \pm 0.07$ | $0.27 \pm 0.12$ | $0.21 \pm 0.09$ |
|      | Total    | $0.66 \pm 0.12$ | $0.63 \pm 0.12$ | $0.74 \pm 0.14$ | $0.68 \pm 0.14$ |
| Ne... | Total    | $0.75 \pm 0.20$ | ... | ... | ... |

Note.—All abundance values are in units of the solar values of Anders & Grevesse 1989.

$^a$ Volume filling factor of 0.2 is assumed for the WIM. No correction is made for dust scattering.

$^b$ Volume filling factor of 1.0 is assumed for the WIM as an extreme case. No correction is made for dust scattering.

$^c$ Volume filling factor of 0.2 is assumed for the WIM. Correction considered to be the maximum is made for dust scattering.

$^d$ Volume filling factor of 1.0 is assumed for the WIM as the extreme case. Correction considered to be the maximum is made for dust scattering.

$^e$ The abundance of gas-phase O does not depend on the cases considered.
Gans approximation is valid only for $a_{\text{max}} \lesssim 0.1 \mu m$ and the scattering cross section saturates at $a_{\text{max}} \gtrsim 0.1 \mu m$ (Alcock & Hatchett 1978; Smith & Dwek 1998). Thus, the correction factor does not increase for larger grains, and the correction factor applied above can be regarded as the maximum correction.

The O abundance values calculated for four different cases (with and without correction for dust scattering and with two different values of the volume filling factor of the WIM) are summarized in Table 4. The total O abundance is between $0.63 \pm 0.12$ and $0.74 \pm 0.14$ times solar. On the other hand, the Ne abundance is $0.75 \pm 0.20$. Our results are more consistent with the recent solar abundances than the most widely used “old” values. For example, the O and Ne solar abundances by Holweger (2001) are 0.65 and 0.81 times the values in Anders & Grevesse (1989), respectively.

Another important parameter we can estimate from the present X-ray observation is the gas-to-dust ratio of the O column densities, which is estimated to be $2.2^{+1.3}_{-1.1}$, $2.8^{+1.5}_{-1.1}$, $1.7^{+1.0}_{-0.9}$, and $2.2^{+4.0}_{-1.1}$ for cases 1–4 of Table 4, respectively. This should be compared with the gas/dust ratios estimated from the gas abundance assuming that the total abundance is solar. The O gas abundance is determined from interstellar UV absorption lines (Cartledge et al. 2001). Adopting the solar abundance of Anders & Grevesse (1989) results in a gas/dust ratio of 0.7, while adopting that of Holweger (2001) yields a ratio of 1.7. Our result is again consistent with the latest solar abundance value.

For O, the present X-ray result contains an additional uncertainty due to the correction for dust scattering. We can avoid this if we include the spectrum from the scattering halo in the analysis. This requires nondispersive, high-resolution spectrometers, such as microcalorimeters, which will be used on board future X-ray missions, such as Astro-E2.

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