

THE FIRST HIGH-RESOLUTION X-RAY SPECTRUM OF CYGNUS X-1: SOFT X-RAY IONIZATION AND ABSORPTION

N. S. SCHULZ,¹ W. CUI,² C. R. CANIZARES,¹ H. L. MARSHALL,¹ J. C. LEE,¹ J. M. MILLER,¹ AND W. H. G. LEWIN¹

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ABSTRACT

We observed the black hole candidate Cyg X-1 for 15 ks with the High-Energy Transmission Grating Spectrometer aboard the *Chandra X-Ray Observatory*. The source was observed during a period of intense flaring activity, so it was about a factor of 2.5 brighter than usual, with a 0.5–10 keV (1–24 Å) luminosity of 1.6×10^{37} ergs s⁻¹ (at a distance of 2.5 kpc). The spectrum of the source shows prominent absorption edges, some of which have a complicated substructure. We use the most recent results from laboratory measurements and calculations to model the observed substructure of the edges. From the model, we derive a total absorption column of $(6.21 \pm 0.22) \times 10^{21}$ cm⁻². Furthermore, the results indicate that there are ~10%–25% abundance variations relative to solar values for neon, oxygen, and iron. The X-ray continuum is well described by a two-component model that is often adopted for black hole candidates: a soft multicolor disk component (with $kT = 203$ eV) and a hard power-law component (with a photon index of ~2). Comparing the fit results to those of the hard and soft states, we conclude that the source was in a transitional state. Finally, the spectrum also shows the presence of faint emission lines, which could be attributed to highly ionized species.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — stars: individual (Cygnus X-1) — techniques: spectroscopic — X-rays: stars

1. INTRODUCTION

Cygnus X-1 was the first X-ray source to be identified with a binary system and where radial velocity measurements indicated a mass of the compact companion large enough to be a black hole rather than a neutron star (Webster & Murdin 1972; Bolton 1972). The period of the binary was determined optically to be about 5.6 days. The system consists of an O9.7 Iab supergiant with a mass in excess of $\sim 20 M_{\odot}$ in orbit with a black hole of a mass in excess of $\sim 7 M_{\odot}$ (see Tanaka & Lewin 1995 for a detailed review). Cyg X-1 is therefore intrinsically different from the majority of known black hole candidates (BHCs) whose stellar components, where known, are much less massive. Nevertheless, Cyg X-1 is generally regarded as an archetypical BHC; its spectral and temporal properties are often used to identify other BHCs, although so far the only direct evidence for the black hole nature comes from the dynamical determination of its mass via radial velocity measurements. The X-ray emission from Cyg X-1 is likely due to the release of gravitational energy of matter that is accreted by the black hole from the companion star. The mass accretion process is thought to be mediated by a so-called focused wind from the companion star that is close to but not quite filling its Roche lobe (Gies & Bolton 1986). Tentative evidence for wind accretion is provided by the observed orbital modulation of X-ray and radio emission from Cyg X-1 (Kitamoto et al. 2000; Wen et al. 1999; Brocksopp et al. 1999a; Priedhorsky, Brandt, & Lund 1995; Holt et al. 1979).

In the soft (<10 keV) X-ray band, the X-ray spectrum of Cyg X-1 can be described roughly by a two-component model: a multicolor disk component and a power-law component. The former accounts for the X-ray emission from

the hot inner portion of an optically thick, geometrically thin accretion disk, while the latter is thought to be due to inverse Comptonization of soft photons (e.g., from the accretion disk) by energetic electrons in an optically thin configuration. The exact shape of the continuum defines two distinct spectral states for Cyg X-1: the hard and the soft state. The source is usually found in the hard state, where the spectrum is dominated by the power-law component with a photon index of ~ 1.7 (see review by Tanaka & Lewin 1995 and references therein). The detection of the weaker disk component is difficult during this state. The most reliable results came from the observations of the source with *ASCA* (Ebisawa et al. 1996), which gave a temperature of the disk of only about $kT = 100$ eV.

Occasionally, for yet unknown reasons, Cyg X-1 experiences a transition to the soft state, where the disk component grows stronger and the power-law component steepens to a typical photon index of about 2.5 (Tanaka & Lewin 1995). The most recent spectral state transition occurred in 1996 (Cui et al. 1997). The source was observed simultaneously by *ASCA* and the *Rossi X-Ray Timing Explorer (RXTE)* near the end of the hard-to-soft transition. The results indicated that the disk component was indeed dominant below 10 keV, and the temperature of the disk was around $kT = 400$ eV (Cui et al. 1998).

The detection of an iron $K\alpha$ line and/or absorption edge has been reported for Cyg X-1. For instance, a broad emission line seen at ~ 6.2 keV was interpreted to be a redshifted and broadened $K\alpha$ line of cold iron (Barr, White, & Page 1985; Tanaka 1991; Done et al. 1992). A narrow emission line was also detected at 6.4 keV in the hard state, which is thought to originate in the fluorescent emission from the cold part of the accretion disk (Kitamoto et al. 1990; Tanaka 1991; Ebisawa et al. 1992, 1996). A similar emission line was also seen near the soft state (during the 1996 state transition) but at ~ 6.6 keV, which was interpreted as emission from highly ionized iron (Cui et al. 1998). Iron $K\alpha$ line emission has become one of the most useful tools for

¹ Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139.

² Department of Physics, Purdue University, West Lafayette, IN 47907.

probing the strong gravitational field near a black hole. The detection of a gravitationally distorted line would provide strong evidence for the existence of a black hole. Such a line has been reported for the Seyfert 1 galaxy MCG-6-30-15 (Tanaka et al. 1995) but has never been detected in Cyg X-1.

In this paper we present the first high-resolution X-ray spectra of Cyg X-1 obtained with the High-Energy Transmission Gratings Spectrometer (HETGS; C. Canizares et al. 2002, in preparation) on board the *Chandra X-Ray Observatory* during its early phase of the mission. In this paper we take a fresh look at the soft part of the spectrum below 10 keV, particularly below 1 keV. We report the detection of prominent absorption edges in the spectrum of Cyg X-1, as well as weak emission lines owing to highly ionized species.

2. CHANDRA OBSERVATIONS AND DATA REDUCTION

Cyg X-1 was observed with the HETGS on 1999 October 15 (start time 05:47:21 UT) continuously for 15 ks. For a general description of the HETGS we refer to available *Chandra X-Ray Center* (CXC) documents.³ In this section we outline the overall properties of this observation, which was performed using the Advanced CCD Imaging Spectrometer (ACIS; G. Garmire et al. 2001, in preparation) in standard timed event mode but with alternating frame times to accommodate the high source flux.

The HETGS disperses about half of the incident photons into first- and higher order spectra, which are recorded with an array of six CCDs at the focal plane of the telescope. All other photons generate an image in the zeroth order, which is located at the focus of the telescope. Every set of seven CCD frames of 3.3 s was followed by a short frame of 0.5 s. This resulted in an effective exposure of 11.5 ks in long-frame mode and 0.3 ks in short-frame mode. Separate event lists were delivered by the CXC standard processing. Throughout this paper, we distinguish between a long-frame and a short-frame observation, although the reader should always keep in mind that both observations were performed during the same time period. In order to avoid frame dropouts owing to telemetry saturation, we blocked the zeroth-order events electronically from being transmitted. Therefore, standard source detection is not possible, and we ignored any products from standard processing higher than level 1.

The determination of the zeroth-order position is crucial for the calibration of the wavelength scales because this position defines its zero point. We calculated this position by fitting the dispersed images of the medium-energy gratings (MEGs) and high-energy gratings (HEGs) and then determined the intersections of the fit with the zero-order readout trace of the CCD. The intersections for the MEG and HEG were determined to be within 0.2 detector pixels. From this, we deduce an accuracy of the zero-order position of 0.002 Å in MEG and 0.001 Å in HEG first order. This uncertainty is negligible when compared to the overall wavelength calibration, which has been verified on orbit to be better than ~0.05% (C. Canizares et al. 2001, in preparation). The worst case uncertainty in the wavelengths then is 0.011 Å in the MEG first order near the O K edge, 0.008 Å in the HEG first order near the Ne K edge, and 0.003 Å in the MEG third order near the Mg K edge. We

processed the event lists into grating (level 1.5) event lists using available CXC software. From there on we used the *Chandra Interactive Analysis of Observations* (CIAO 2.1⁴) package and custom software to produce our final grating spectra. We computed aspect-corrected exposure maps for each spectrum that allow us to calculate the effective area of the spectrometer to obtain absolute fluxes. Current systematic uncertainties of the effective area calibration are ~10%–20%; in some cases we were able to correct for local flux enhancements by comparing opposite sides of the dispersion.

High X-ray fluxes cause photon pileup in X-ray CCD devices. In the case of Cyg X-1 the flux is so high that photons pile up even in the grating spectra during long-frame exposures. Pileup occurs when two or more photons of the same energy are registered almost simultaneously and thus identified by the CCD device as one photon of the summed energies of the registered photons. In the case of the grating spectra, this means that photons from first-order spectra are registered in higher CCD channels that are coincidentally identified for photons from higher order spectra. The first-order spectra below ~14 Å (MEG) and ~10 Å (HEG) are depleted of photons, which then populate the second- and third-order spectra at wavelengths below $\frac{1}{2}$ and $\frac{1}{3}$ of the wavelengths, respectively. The MEG third-order spectrum below ~4.6 Å is therefore “contaminated” by photons piled up from MEG first order.

3. LIGHT CURVE

Cyg X-1 was observed during a period when it produced frequent X-ray flares. Flaring activity is common for the source, as shown by the long-term monitoring of the source by the all-sky monitor (ASM) aboard *RXTE* (see Fig. 1). However, X-ray flares are usually brief and are therefore difficult to catch in short observations. Consequently, they are poorly understood owing to the lack of data. The *Chandra* observation now provides us with a rare opportunity to examine the properties of Cyg X-1 during such an event. Figure 1 shows a portion of the ASM light curve for a time span of about 100 days during which the

⁴ See <http://cxc.harvard.edu>.

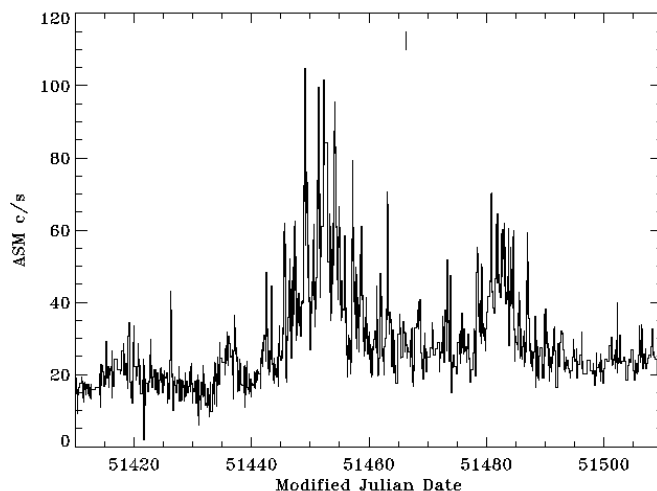


FIG. 1.—ASM light curve of Cyg X-1 of the soft flares in the vicinity of the HETGS observation. The vertical line at the top indicates the time of the *Chandra* observation.

³ See <http://asc.harvard.edu/udocs/docs/docs.html>.

short (15 ks) *Chandra* observation was performed. The time of the *Chandra* observation is indicated in the figure. As can be seen, Cyg X-1 was engaged in heavy flaring activity, and the observation lies in between two giant flares. We also note that there are gaps in the ASM coverage. Some brief miniflares could therefore have been missed during the ASM coverage. The *Chandra* light curve is difficult to analyze because the source appeared at a rate of over 200 counts s^{-1} in the HETGS first orders, and light curves are systematically affected when we include these data. Excluding all grating data affected by pileup (with a confidence level of better than 99.9%), we obtained a light curve for the bandpass above 6 Å, which showed variability of roughly 20% over the observation.

4. SPECTRAL ANALYSIS

Major portions of the first-order grating spectra were severely piled up and only of limited quality, and not all wavelengths can be used to study the broadband continuum shape in the long-frame observation. In the following analysis, we look in detail at the observed neutral edges from which we are able to derive reliable column densities of the absorbing material. We use these column densities to fit the spectral continuum in the subsequent section. Using the optical depth of each detected edge from the spectrum, we derive the column density for that particular element. Using the combined results for various elements, we then determine an overall column density, as well as abundance variations of the elements in the absorbing gas. Finally we identify residual absorption and emission features.

4.1. Photoelectric Absorption

In low-resolution detectors the detailed shape of photoelectric absorption edges were never resolved and therefore were largely ignored. In a high-resolution spectrum of the Crab Nebula using the focal-plane crystal spectrometer on board *Einstein*, Schattenburg & Canizares (1986) presented the first detailed X-ray spectrum near the O K edge and found marginal evidence for a resonant $1s-2p$ absorption line from atomic oxygen. Paerels et al. (2001) showed with *Chandra* Low-Energy Transmission Grating (LETG) data near the neutral oxygen edge of another X-ray binary, 4U 0614+091, that there is considerable structure owing to absorption lines from atomic oxygen as well as other molecular compounds. For the case of Cyg X-1, we observe similar complex substructures, which we quantify by comparing them with expected structure obtained from laboratory measurements as well as from calculations.

The MEG count spectrum (Fig. 2) shows the photoelectric absorption edges of O K, Fe L, and Ne K of Cyg X-1. A detailed study of the structure of photoelectric absorption in observations of a sample including other bright X-ray binaries will be presented by Schulz et al. (2001).

Neutral absorption column densities are directly proportional to the optical depth of the neutral edge. The latter is defined by

$$\tau = \ln(f_{\text{high}}/f_{\text{low}}), \quad (1)$$

where f_{high} is the X-ray flux on top of the edge at the high-wavelength side and f_{low} is the X-ray flux at the bottom of the edge at the low-wavelength side. We emphasize that this optical depth corresponds to the total amount of photoelectric absorption, which includes the interstellar medium in

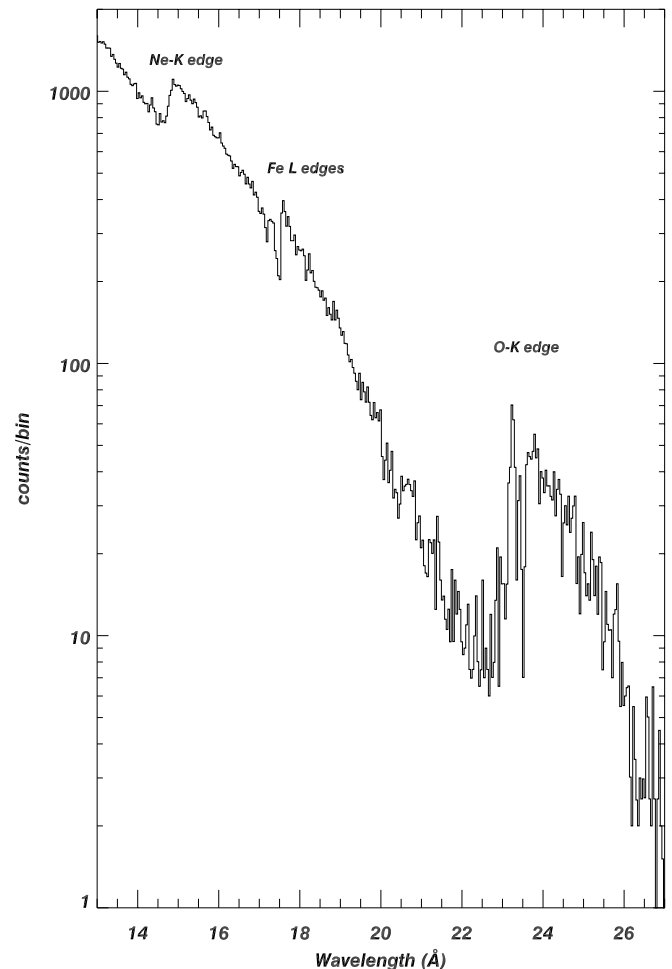


FIG. 2.—MEG spectrum in the 13–27 Å band, where it is unaffected by pileup. The bin size is 0.04 Å. The data are not corrected for instrumental effects.

the line of sight as well as a possible intrinsic contribution by the source itself. We observe edges at O, Fe, Ne, and Mg. The data allow us to directly measure the optical depths in the cases of O, Fe, and Ne. The Mg edge is visible, but the bins for f_{high} and f_{low} have large uncertainties. The Si edge does not appear significantly in the data. Table 1 shows the expected and measured values of the edges and the measured optical depths from these edges. We quadratically added a systematic uncertainty of one spectral resolution bin to the wavelength uncertainty, which also dominates the uncertainty of the edge value.

The edges exhibit considerable substructure, which we describe in detail below. We first determined the optical depths τ of the O-K, Fe-L, and Ne-K edges using equation (1). The optical depth ratios between these edges showed some deviations to the ones expected for abundances derived using the polynomial fit parameters from Morrison & McCammon (1983) as implemented in XSPEC using the cross sections from Verner et al. (1993). We also applied a continuum model fit derived from the short-frame data using a predetermined value for N_{H} derived mainly from a first assessment of the Ne-K optical depth, which shows the least structure. Assuming a solar abundance relative to hydrogen as stated by Morrison & McCammon (1983), we find a best value of $N_{\text{H}} = 6.21 \pm 0.22 \times 10^{21} \text{ cm}^{-2}$. For elements other than Ne, O, and Fe we use the solar abun-

TABLE 1
POSITIONS AND OPTICAL DEPTHS FROM PHOTOELECTRIC EDGES

Edge	λ_o (Å)	λ_m (Å)	τ_m	NH_z (cm^{-2})	a_z^a
O K	23.34 ^b	23.15 ± 0.02	2.226 ± 0.133	$(3.92 \pm 0.23) \times 10^{18}$	0.93
Fe L 3	17.51 ^c	17.56 ± 0.02	1.098 ± 0.086	$(1.55 \pm 0.12) \times 10^{17}$	0.75
Fe L 2	17.19 ^c	17.23 ± 0.02	0.307 ± 0.027	$(1.46 \pm 0.12) \times 10^{17}$...
Fe L 1	14.66 ^b	14.66 ± 0.02	0.079 ± 0.017
Pure Fe L	17.44 ^d	17.41 ± 0.02	0.058 ± 0.012	$(8.24 \pm 1.72) \times 10^{15}$...
Fe _x O _y	17.64 ^e	17.66 ± 0.02	0.025 ± 0.009	$(4.49 \pm 1.61) \times 10^{15}$...
Ne K	14.30 ^b	14.32 ± 0.02	0.343 ± 0.011	$(9.43 \pm 0.32) \times 10^{17}$	1.11
Mg K	9.50 ^b	9.49 ± 0.02	0.088 ± 0.032	$(3.67 \pm 1.34) \times 10^{17}$	1.00
Si K	6.74 ^b	6.74 ± 0.01	0.036 ± 0.028	$(2.31 \pm 1.81) \times 10^{17}$	1.00

^a Abundance adjustment factor.

^b Bearden & Burr 1967.

^c Kortright & Kim 2000.

^d M. L. Brown 2000, private communication.

^e Crocombette et al. 1995.

dances relative to hydrogen. In the case of Ne, O, and Fe we use the long-frame data to tweak the optical depths by adjusting abundances. The abundance adjustment factor a_z is shown in Table 1. For O and Fe we find a lower abundance of $\sim 7\%$ and $\sim 25\%$, respectively. For Ne we find a higher abundance of 11%. From the final adjusted models we then determined the optical depths τ_m shown in Table 1. We have also calculated the column density for each ion species Z , defined as

$$N_z = \frac{\tau_m}{\sigma_z}, \quad (2)$$

where σ_z are the atomic photoelectric cross sections. We use mostly the cross sections from Verner et al. (1993), except for Fe, where we have new cross sections from Kortright & Kim (2000). The final spectral model was generated by computing the absorption edges using τ_m and also by adding single Gaussians for local absorption dips.

4.1.1. The O K Edge

Structure in the O K edge is difficult to assess with the MEG because the effective area of the instrument is relatively low and affected by instrumental O features. The source is easily detected longward of the edge (see Fig. 2); statistical uncertainties in the data are on the order of less than 30% (Fig. 3). Shortward of the edge, the spectrum is very faint. The most probable position of the O K edge appears at 23.15 Å, which is lower than the expected value of 23.31 Å (Bearden & Burr 1967) but consistent with a most recent observation of Cyg X-1 (Marshall et al. 2002). The value of the O edge in this observation is difficult to assess, because we observe excess emission around 23 Å. We consider two likely interpretations. First, the excess emission would result from a systematic error in the effective area model (see Fig. 3, *inset*), which is dominated by the O K edges of polyimide in the ACIS filter and the MEG support material. On the basis of prelaunch calibration, however, systematic errors in the HETGS effective area should be no more than 50%, while an error 4 times or more would be required to eliminate the feature at 23 Å. Second, we cannot rule out the possibility that some of the excess emission consists of emission lines from Cyg X-1 (see § 4.3). Given the results by Marshall et al. (2002), the latter interpretation is more likely. The feature at 23.36 Å coincides with a resonance feature in polyimide, but there is a

significant residual, which may be identified with the 1s–2p transition from oxygen in Fe₂O₃ (Wu et al. 1997). Most prominently, the large absorption dips with an FWHM of 0.08 Å at 23.51 Å owing to the 1s–2p transition in atomic oxygen. This feature was marginally detected by Schattenburg & Canizares (1986) in a Crab Nebula observation but appeared prominently in the LETG observation of X0614+091 (Paerels et al. 2001).

4.1.2. The Fe L Edges

Iron is the most abundant element that has its L absorption in the HETGS bandpass. The Fe-L1 edge is due to transitions from the 2s level, Fe-L2 from the 2p_{1/2}, and Fe-L3 from the 2p_{3/2} level. The Fe-L3 edge is usually strongest; the Fe-L1 edge is weakest. Figure 4 shows the Fe-L edge region in the MEG spectrum. We clearly observe that these edges have narrow absorption features, which cannot be described by a single step function. The Fe-L1 edge region is shown in Figure 5. The shapes of the Fe-L edges were measured by various groups using metallic iron of various purity as well as iron oxides (Kortright & Kim 2000; M. L. Brown 2000, private communication;⁵ Schwickert et al. 1998; Crocombette et al. 1995). These studies

⁵ See <http://www-mp.phy.cam.ac.uk>.

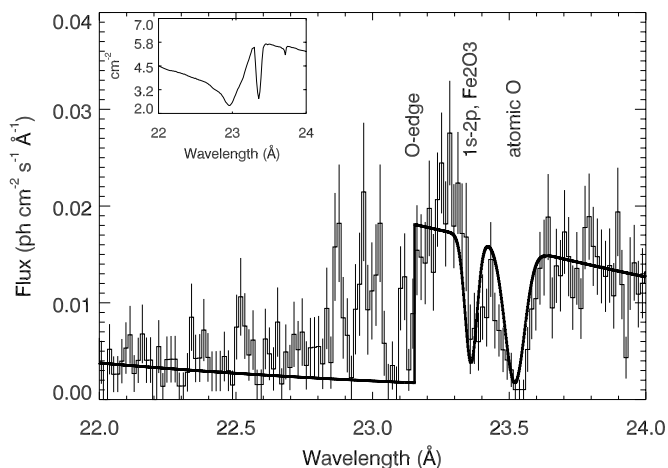


FIG. 3.—MEG view of the O K edge region. The curve represents the model. The inset shows the effective area of the MEG around the O K edge.

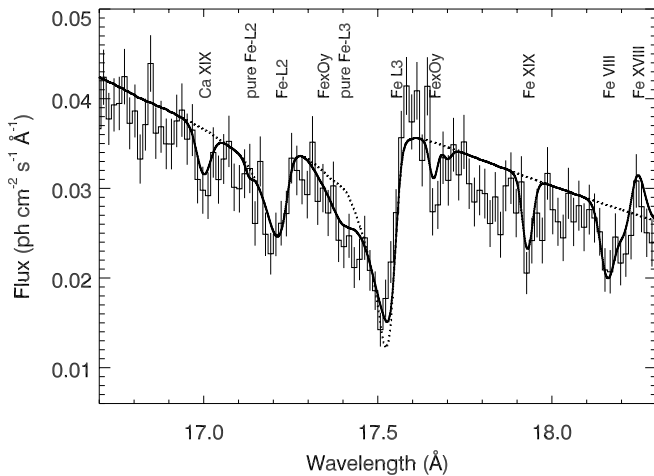


FIG. 4.—Portion of the MEG spectrum showing the photoelectric Fe L3 and L2 edges. The solid curve is the final model; the dotted line shows the shape of the edges from Kortright & Kim (2000).

indicate that the position of the Fe L edges depend on whether the sample is oxidized or metallic. We measured the position of the Fe L3 edge (defined to be the top of the edge) to be 17.56 \AA . This position is consistent with recent measurements of metallic Fe film by Kortright & Kim (2000) but is between results from Fe foils of very high purity (M. L. Brown 2000, private communication) and Fe oxides (Crocombette et al. 1995). We used new experimental cross sections from Kortright & Kim (2000) in the absorption model shown in Figure 4. This model represents the overall observed shape of the edges quite well, with some caveats. First of all, the column density of Fe is $\sim 25\%$ lower than expected from the Morrison & McCommon representation. We observe some slight deviations from the shape predicted by Kortright & Kim (2000), which may indicate that Fe exists in various forms, or that the edge has superposed intrinsic emission and absorption lines. We observe additional but very weak features around 17.41 and 17.66 \AA , which match the positions that M. L. Brown (2000, private communication) determined from an extremely pure Fe sample as well as those from Fe oxides (Crocombette et al. 1995), respectively. We added absorption from these forms

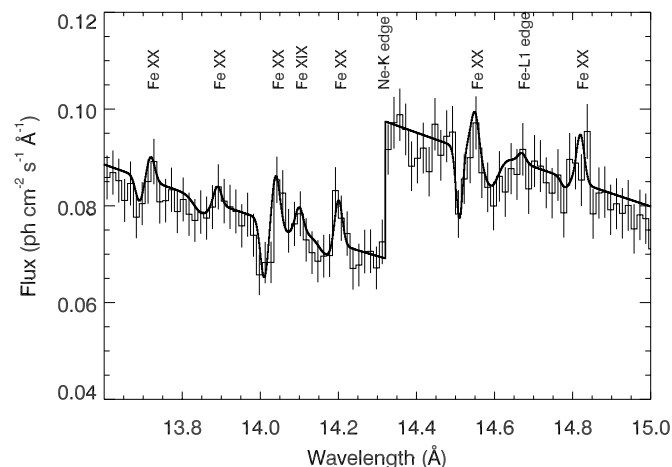


FIG. 5.—Portion of the MEG spectrum that shows the photoelectric edge of Ne K and numerous weak ionized iron lines.

of Fe into the model assuming the same shape of the cross section as from the Kortright data. With this approach we would recover about 7% of the missing Fe. Wilms, Allen, & McCray (2000) list an amount comparable to the remaining 18% as the difference between the solar abundance of Fe and the one in the interstellar medium. There are also faint features from ionized species (see § 4.3), which appear in emission as well as absorption. From our analysis in § 4.3 it seems likely that these distortions are due to emission and absorption from highly ionized iron, so we simply added Gaussian line components to the model. The normalizations were determined by fitting single Gaussians to the data, while the widths were fixed to the MEG spectral resolution.

4.1.3. The Ne K-, Mg K-, and Si K Edges

The Ne K edge (see Fig. 5) can be very well modeled using the Verner et al. (1993) cross section, since it appears only in gaseous form. The wavelength has been measured in the laboratory to $14.302 \pm 0.003 \text{ \AA}$ in agreement with the calculated value of 14.30 \AA (Bearden & Burr 1967). We measure a value of $14.32 \pm 0.02 \text{ \AA}$, which is consistent with the expected value above. It is also consistent with the value observed in X0614+091 (Paerels et al. 2001), which however has a very large uncertainty. There is considerable substructure in the vicinity, which we identify as emission lines (see § 4.3) similar to the features in the vicinity of the O and Fe edges.

The Mg K and Si K edges (see Fig. 6) appear at wavelengths where the MEG and HEG spectra are significantly piled up, and we have to rely on the spectrum from the MEG third order, which has an order of magnitude lower efficiency. Both edges are modeled using the Verner et al. (1993) cross sections, and the abundance factor a_z in Table 1 is set to 1.

4.2. The X-Ray Continuum

For the determination of the continuum spectral shape we use the short as well as the full-frame observations. The short-frame data provide us with a pileup-free continuum at the expense of exposure. We therefore determined the continuum in two steps. First we fit the spectra from the short-

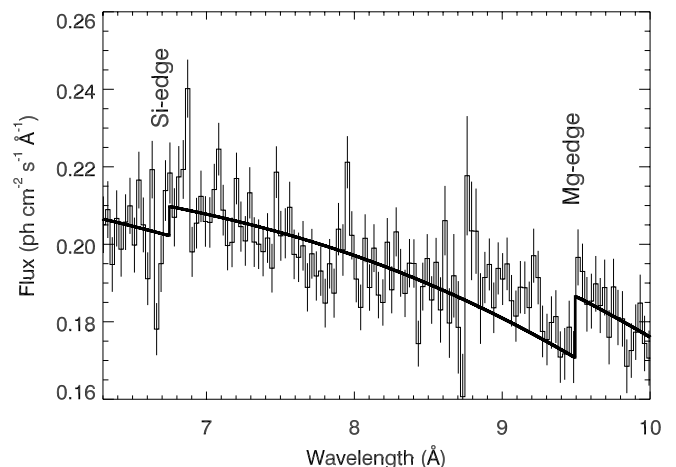


FIG. 6.—Portion of the MEG third-order spectrum that shows the photoelectric edges of Mg K and Si K.

frame observation using the XSPEC package in order to determine the overall spectral shape and also define the spectral model to fit the continuum. Second, we test the fit on a spectrum obtained by combining pileup-free portions of the long-frame observations, where we combine portions from the MEG first (14–26 Å), HEG first (10–14 Å), and MEG third (6–10 Å) orders. Both short-frame and long-frame spectra have their limitations: the short-frame spectra have large statistical uncertainties; the long-frame data are statistically very significant but only accurate for wavelengths greater than 6 Å.

A simple power law does not give a good fit even to the short-frame data. A second power-law component improved the fit to the short-frame data considerably but leaves significant residuals when applied to the long-frame data. Using the multicolor disk model (as used by Cui et al. 1997) as a second component we obtain an excellent fit to the data ($\chi^2 < 1$; 2206 degrees of freedom). The result, shown in Figure 7, also includes the photoelectric absorption models. The power law has an index of 1.95 ± 0.07 ; the disk component has a temperature of $kT = 203 \pm 4$ eV. The total absorbed flux is 1.03×10^{-8} ergs cm^{-2} s^{-1} between 0.5 and 10 keV ($\sim 1\text{--}25$ Å), with the disk component contributing about 11%. Assuming a distance of 2.5 kpc to the source, we determine a luminosity of the disk blackbody component of 5.34×10^{36} ergs s^{-1} and a total luminosity of 1.61×10^{37} ergs s^{-1} . Compared with the properties of the source in the hard and soft states (e.g., Ebisawa et al. 1996, Cui et al. 1998), our results clearly show that the source was in a transitional state, as expected from the ASM light curve (see Fig. 1).

4.3. Narrow Emission and Absorption Features

There are a variety of emission and absorption features in the vicinity of the edges (Figs. 3–5). A few are also visible in Figure 7. Nearly all of these features are weak, detected with a signal-to-noise ratio (S/N) of less than 5. The S/N in Table 2 is defined as

$$S/N = \frac{\sum f_i^l}{\sqrt{\sum (\sigma_i^c)^2}}, \quad (3)$$

where f_i^l is the flux of a line in the spectral bin i and σ_i^c the significance of the continuum in that bin and the sum is over the line width. The flux in each bin is the value of the bin subtracted by the value of the model in that bin multiplied by the width of the bin. The uncertainty in each bin of the underlying continuum was determined from the square root of the model value folded through exposure and effective area. We exclude all bandpass regions where pileup effects are significant. The detected emission, as well as absorption features and the positions (λ_{em} for emission, λ_{abs} for absorption), tentative identifications, and detection significances are listed in Table 2. The identifications were made using the line list from Mewe (1994). Features with an S/N near 2 are not very significant but in the context of the ones with higher ratios have valid identifications. We identify ion species mostly from intermediate to highly ionized Fe with ionization stages between Fe xviii and Fe xxiv. In column (3), we also list the temperature corresponding to the peak emissivity of the transition. These indicate temperature values between 1.5 and 20 million K. Many of the features are seen in Figures 3–5, but we also show the 11.5–13.6 Å bandpass from the HEG spectrum in Figure 8. All

TABLE 2
WEAK- AND NARROW-LINE FEATURES FOR WAVELENGTHS GREATER THAN 6 Å

λ_{em}^a (Å)	Ion	$\log T^b$ (K)	S/N	λ_{abs}^a (Å)	Ion	S/N
(1)	(2)	(3)	(4)	(5)	(6)	(7)
6.88	Si x	6.3	3.4	6.65	Si xiii	4.1
7.09	Mg xii	7.0	3.3			
7.31	Mg xi	6.8	2.3			
	Ni xxv	7.2				
7.47	Mg xi	6.8	2.1			
	Fe xxiii	7.2				
7.68	Fe xxiii	7.2	...			
7.98	Fe xxiv	7.3	3.2			
				8.05	Fe xxii	2.1
				8.19	Fe xxii	3.0
				8.42	Mg xii	2.3
				8.72	Fe xxiii	2.8
8.76	Fe xxiii	7.2	2.8			
9.22	Mg xi	6.8	4.3			
				10.15 ...	Fe xx	3.1
				10.65 ...	Fe xxiii	5.3
11.67 ...	Fe xviii	6.8	2.3			
11.84 ...	Fe xxii	7.1	2.3			
11.88 ...	Fe xviii	6.9	3.3			
				12.01 ...	Fe xxi	2.4
12.14 ...	Ne x	6.8	2.2			
				12.48 ...	Fe xxi	4.2
12.50 ...	Fe xxii	7.1	2.9			
				12.94 ...	Fe xx	4.5
				12.99 ...	Fe xx	4.4
13.04 ...	Fe xxii	7.1	2.5			
13.14 ...	Fe xx	7.0	2.2			
				13.50 ...	Fe xx	2.0
13.56 ...	Ne ix	6.6	2.1			
	Fe xx	7.0				
				13.69 ...	Fe xx	2.3
				14.02 ...	Fe xix	3.1
14.04 ...	Fe xx	7.0	3.0			
14.20 ...	Fe xx	7.0	3.3			
				14.49 ...	Fe xix	4.7
14.55 ...	Fe xx	7.0	4.1			
14.83 ...	Fe xx	7.0	2.1			
16.42 ...	Fe xx	7.0	3.0			
				17.00 ...	Ca xix	3.6
				17.41 ...	Fe xviii	3.0
17.54 ...	Fe xix	6.9	3.8			
				17.93 ...	Fe xix	4.3
				18.18 ...	Fe xviii	4.4
18.25 ...	Fe xviii	6.8	2.7			
				18.81 ...	?	2.8
18.83 ...	O viii ^c	6.5	2.0			
21.43 ...	O vii ^c	6.3	3.4			
22.52 ...	O v	6.2	2.7			
22.86 ...	O iv	5.7	4.1			
23.05 ...	S xiv	6.5	3.3			
23.10 ...	S xiii	6.4	3.5			

^a From SPEX 1999 line list.

^b Temperature of maximum emissivity.

^c Possibly blueshifted by 2350 km s^{-1} .

the features are narrow and do not appear resolved by the MEG resolution. The observed flux range is $(2.1\text{--}15) \times 10^{-5}$ ph cm^{-2} s^{-1} .

There are several difficulties associated with the identifications of these weak lines. In Figures 3–8 we see that there

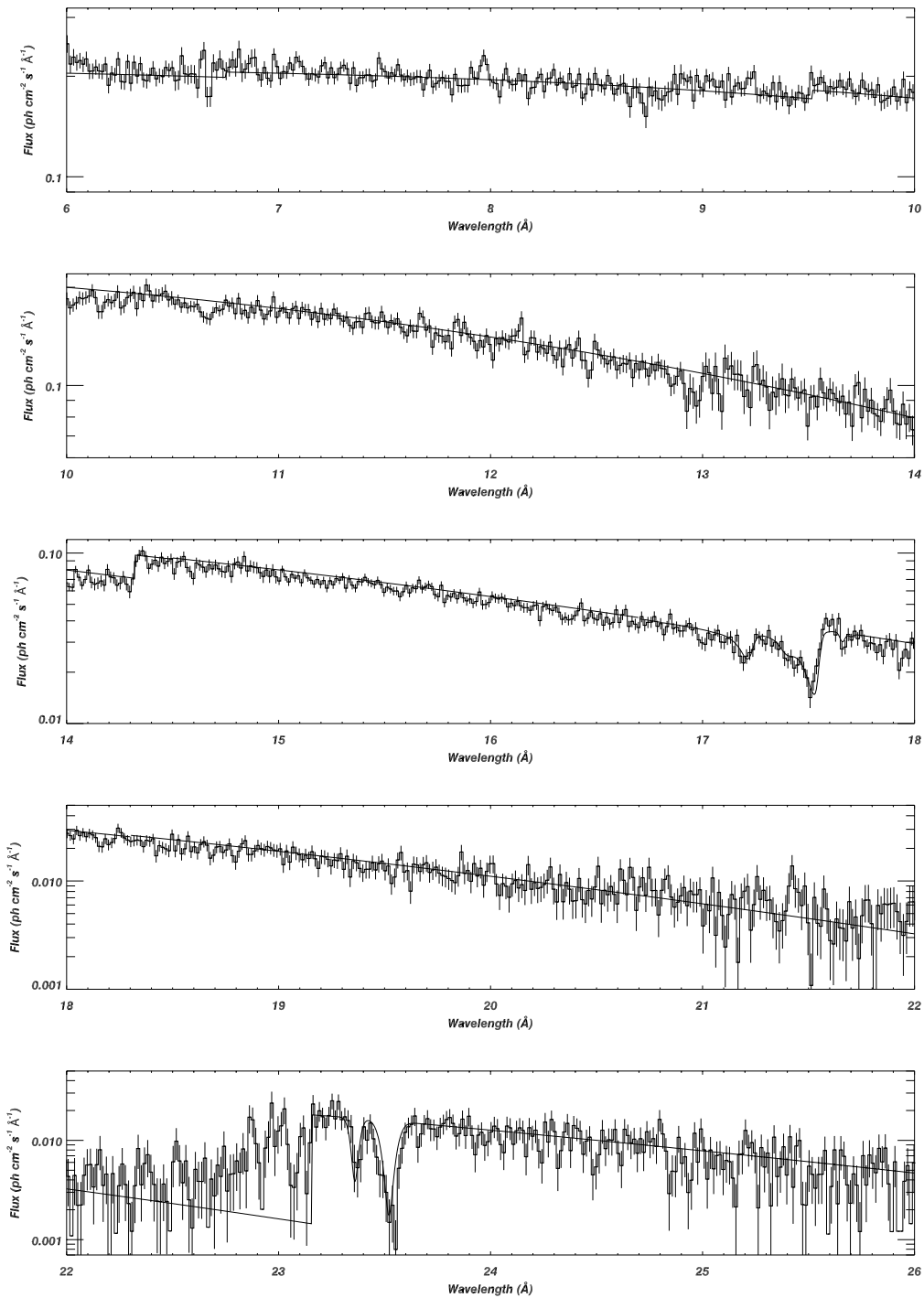


FIG. 7.—Broadband HETGS spectrum between 6 and 26 Å. The continuum model was fitted with a disk blackbody plus power-law model. The lower three panels are from the MEG first-order spectrum, the second from the top shows a portion of the HEG first-order spectrum, and the top panel shows the MEG third-order spectrum.

are also absorption features, and many of them seem to be associated with an adjacent emission line that gives the impression of a P Cygni type line profile, such as has been observed in Cir X-1 (Brandt & Schulz 2000). We list those in the right part of Table 2. Note that Marshall et al. (2002) also report strong absorption lines in another HETGS observation of Cyg X-1. In general, identifications in the wavelength band below 16 Å are not entirely unique, because the line density is so high, increasing the likelihood of misidentification. At longer wavelengths (> 16 Å), the Fe

transition forest thins so identifications are more straightforward.

Figure 9 shows a weak detection at 21.43 Å. This line coincides with a line from Ca XVI at 21.44 Å, which given the temperature distribution in column (3) of Table 2, is an unlikely identification in the absence of other nearby Ca lines. We tentatively attribute this feature to the O VII He-like resonance line, which would mean a shift corresponding to about -2350 km s $^{-1}$. Similarly, we detect a fainter feature at 18.83 Å, with some absorption at 18.81 Å,

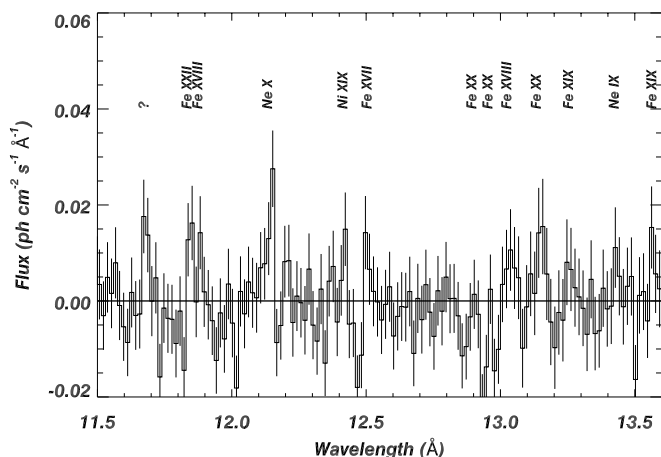


FIG. 8.—Portion of the HEG spectrum between 11.5 and 13.6 Å. Candidate emission and absorption line identifications are dominated by Fe. All marked features are consistent with the MEG response function.

which are both not identified. It could be identified with the O VIII Ly α transition, if it is also blueshifted by 2350 km s $^{-1}$.

5. SUMMARY AND DISCUSSION

The first high-resolution X-ray spectrum of Cyg X-1 obtained with *Chandra* shows various features, which will be discussed in more detail below. In the following we briefly summarize the main results from the *Chandra* observations. From resolved neutral edges of various elements we derive a very accurate column density for Cyg X-1 of $(6.21 \pm 0.22) \times 10^{21}$ cm $^{-2}$. The results indicate that there are abundance variations for Ne, O, and Fe on the order of 10%–20% relative to solar values; the deficiencies in Fe and O are roughly consistent with an abundance distribution of the interstellar medium. The Fe L edges show narrow absorption line structure and for the first time were accurately modeled using most recent laboratory data. These narrow line patterns could have given rise to residuals in the soft band of previous observations of X-ray binaries (Schulz 1999). The spectral continuum is consistent with the models applied to recent *RXTE* spectra. It also shows a complex pattern of emission and absorption lines. The observations do not allow us to uniquely conclude on the origin of these discrete lines.

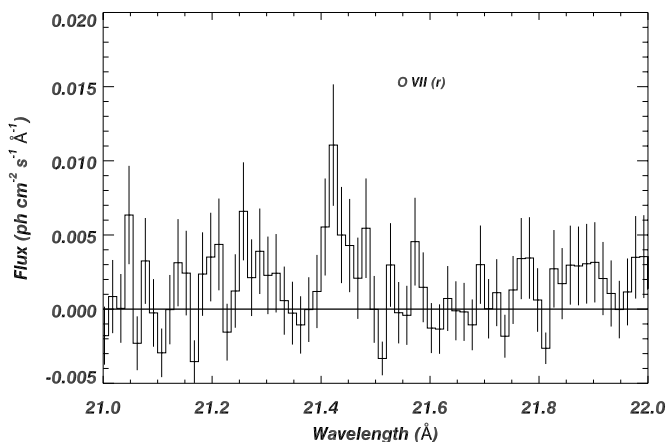


FIG. 9.—Portion of the MEG spectrum showing a possible detection of a blueshifted O VII line.

One of the most immediate benefits of the high spectral resolution in the soft band is that we can measure the amount of photoelectric absorption almost independent of the intrinsic continuum. A column density of 6.2×10^{21} cm $^{-2}$ was already suggested by Balucińska & Hasinger (1991) from *EXOSAT* studies of the soft excess in Cyg X-1. The column density is expected to vary with the phase of the orbital motion because the amount of stellar wind that the line of sight passes through varies (e.g., Wen, Cui, & Bradt 2001). This might explain the lower values obtained by previous studies (e.g., Cui et al. 1998; Ebisawa et al. 1996; Remillard & Canizares 1984). Using the most updated ephemeris of Cyg X-1 (Brocksopp et al. 1999b), we found that our observation corresponds to an orbital phase of 0.92, which is very close to the superior conjunction (defined when the phase equals 0). In the discussion on the soft state by Wen et al. (2001) it was argued that absorption at this orbital phase should be much higher than the observed 6.2×10^{21} cm $^{-2}$, perhaps indicating a reduction in absorption caused by a high level of ionization of the wind in the flaring state. On the other hand, we note that the derived column density is also quite close to the expected value from the galactic H I distribution (Dickey & Lockman 1990).

Perhaps the most detailed study of neutral absorption and abundance variations in Cyg X-1 spectra was performed by Ebisawa et al. (1996). In several *ASCA* observations, column densities between 5.3 and 6.0×10^{21} cm $^{-2}$ were observed, as well as an underabundance of oxygen of $\sim 20\%$ and an overabundance of neon of $\sim 40\%$ compared to solar (as adopted by Morrison & McCammon 1983). The *Chandra* observations confirm that there are abundance variations but at only a $\sim 10\%$ level for neon and oxygen. We note that these abundance variations are probably unrelated to abundance variations observed in intrinsically absorbed reflection components as suggested by Done & Zycki (1999), to which our *Chandra* spectra are not sensitive. In fact, measurements of the Fe K edge (Kitamoto et al. 1984; Marshall et al. 1993) can be used to argue that here Fe is overabundant by a factor of 2.

Barr & van der Woerd (1990) found an emission line component at 730 eV with an equivalent width of 370 eV, which was confirmed by Ebisawa et al. (1986) but only as an alternative solution to the abundance variations. Our *Chandra* observations do not show such a strong line feature below 1 keV, and the solution of this puzzle clearly lies in the observed structure of the photoelectric Fe L and O K edges. The narrow structures we observe in the Fe L and O K edges could give rise to residuals in the soft band in observations using low-resolution detectors, which ultimately would be interpreted as line features. The detailed modeling using recent laboratory measurements (Kortright & Kim 2000) is quite successful in explaining the overall appearance of the Fe L edges owing to mostly metallic Fe with maybe some contribution from oxides. There is still an outstanding issue in the model, an 8% effect, in that the shape of the Fe L3 edge is not entirely explained by the new cross sections. However, we determine a specific column density owing to Fe of $(1.55 \pm 0.12) \times 10^{17}$ cm $^{-2}$, indicating an underabundance of 25% with respect to solar. Such an iron depletion may also indicate that some material is bound in large grains (Predehl & Schmitt 1995). On the other hand, in Wilms et al. (2000), a large number of elements representing the interstellar medium are listed

slightly underabundant compared to a solar distribution. The O K edge also shows extensive substructure, and most of the details are consistent with the edge in X0614+091 (Paerels et al. 2001).

The determination of the total amount of neutral absorption is essential for the modeling of the intrinsic continuum. Many broadband models have been applied to Cyg X-1 X-ray spectra in the 1 and 10 keV X-ray band (Cui et al. 1997, 1998; Ebisawa et al. 1996), and most of them involved a soft blackbody or disk blackbody plus a power law. The studies based on low-resolution data always suffer from the inability to disentangle various spectral components, so the results tend to be model dependent. Now the superior spectral resolution of the HETGS allows us to measure the absorption edges accurately. From the edges alone, we derived a reliable column density, independent of continuum modeling. With this reduction of free parameters, we were able to model the continuum much more reliably. The results indicate that the source was in a state that is similar to the transitional period between the hard and soft states. This is consistent with the fact that the source was observed during a period of strong flaring.

The detection of modulations caused by the orbital period in the light curves and hardness ratios of Cyg X-1 (e.g., Wen et al. 1999) can be interpreted as being caused by a varying absorption optical depth through the companion wind with the binary motion. Gies & Bolton (1986) estimated that the terminal velocity of the wind is $\sim 1500 \text{ km s}^{-1}$ based on the radiatively driven wind model of Castor, Abbott, & Klein (1975). Recent *Chandra* observations of stellar winds from massive O stars (Schulz et al. 2000; Kahn et al. 2001; Waldron & Cassinelli 2001) find strong X-ray line emission with luminosities quite similar to the faint line

features we observe in the Cyg X-1 spectrum, and we find it very likely that some of these are signatures from the companion wind. The P Cygni type appearance of some of the lines bolster the case for a wind. P Cygni X-ray lines have been observed in the spectra of Cir X-1 (Brandt & Schulz 2000), as well as—tentatively—in Cyg X-3 (Liedahl et al. 2000). In Cir X-1 the profiles are thought to originate in a high-velocity disk wind, while in Cyg X-3 the extremely strong wind of the Wolf-Rayet companion star may generate such lines. Previously, Pravdo et al. (1980) observed wavelength shifts in *IUE* observations of HD226868, the companion of Cyg X-1. Extreme blueshifts of Si IV and C IV lines up to -1570 and -270 km s^{-1} were attributed to the stellar wind of the companion. However, recent *Chandra* observations of massive O stars have detected much smaller blueshifts (Schulz et al. 2000; Waldron & Cassinelli 2001; Kahn et al. 2001; Cassinelli et al. 2001). It is therefore difficult to associate the derived -2300 km s^{-1} shift of the O VII line with the stellar wind. For Cyg X-1 it seems more likely that we observe line emission from various different emission regions, which produce a complex pattern of emission and absorption in the X-ray spectrum. Future high-resolution observations covering different orbital phases and with longer exposures may be used to identify the features that vary with the orbital motion and thus shed light on their physical origin.

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