# Grating X-ray Spectroscopy of High-Velocity Outflows from Active Galaxies

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**Abstract.** X-ray absorption and emission lines now serve as powerful diagnostics of the outflows from active galaxies. Detailed X-ray line studies of outflows have recently been enabled for a significant number of active galaxies via the grating spectrometers on *Chandra* and *XMM-Newton*. We will review some of the recent X-ray findings on active galaxy outflows from an observational perspective. We also describe some future prospects.

X-ray absorption lines from H-like and He-like ions of C, N, O, Ne, Mg, Al, Si, and S are often seen. A wide range of ionization parameter appears to be present in the absorbing material, and inner-shell absorption lines from lower ionization ions, Fe L-shell lines, and Fe M-shell lines have also been seen. The X-ray absorption lines are typically blueshifted relative to the systemic velocity by a few hundred km $s^{-1}$, and they often appear kinematically consistent with UV absorption lines of C IV, N V, and H I. The X-ray absorption lines can have complex profiles with multiple kinematic components present as well as filling of the absorption lines by emission-line photons. A key remaining uncertainty is the characteristic radial location of the outflowing gas; only after this quantity is determined will it be possible to calculate reliably the amount of outflowing gas and the kinetic luminosity of the outflow.

## INTRODUCTION

Outflows are observed to be ubiquitous in active galactic nuclei (AGN), being seen in objects spanning a range of $\sim 10,000$ in luminosity. They have been studied in the most detail via observations of ultraviolet (UV) resonance lines from moderately ionized gas. In luminous Broad Absorption Line quasars (BALQSOs), outflows are observed to reach velocities up to a few $10^4$ km $s^{-1}$, and they subtend $\approx$ 10–30% of the sky as viewed from the central source. In lower luminosity Seyfert galaxies, outflows are observed $\gtrsim 50\%$ of the time although they have velocities up to only $\approx 10^3$ km $s^{-1}$. These outflows are a major component of the nuclear environment, and they may carry a significant fraction of the accretion power. They may also be important in regulating the growth of the black hole and its host galaxy (e.g., Silk & Rees 1998; Fabian 1999) as well as in injecting matter, energy, and magnetic fields into the intergalactic medium (e.g., Turnshek 1988; Wu, Fabian, & Nulsen 2000; Furlanetto & Loeb 2001; Elvis et al. 2002). The observed outflows are photoionized by the radiation from the central source, and they are probably driven by radiation pressure. Despite their ubiquity and importance, their physical location and origin in the AGN system remain unclear; outflows may arise from winds driven off the surface of an accretion disk (e.g., Murray et al. 1995; Proga,

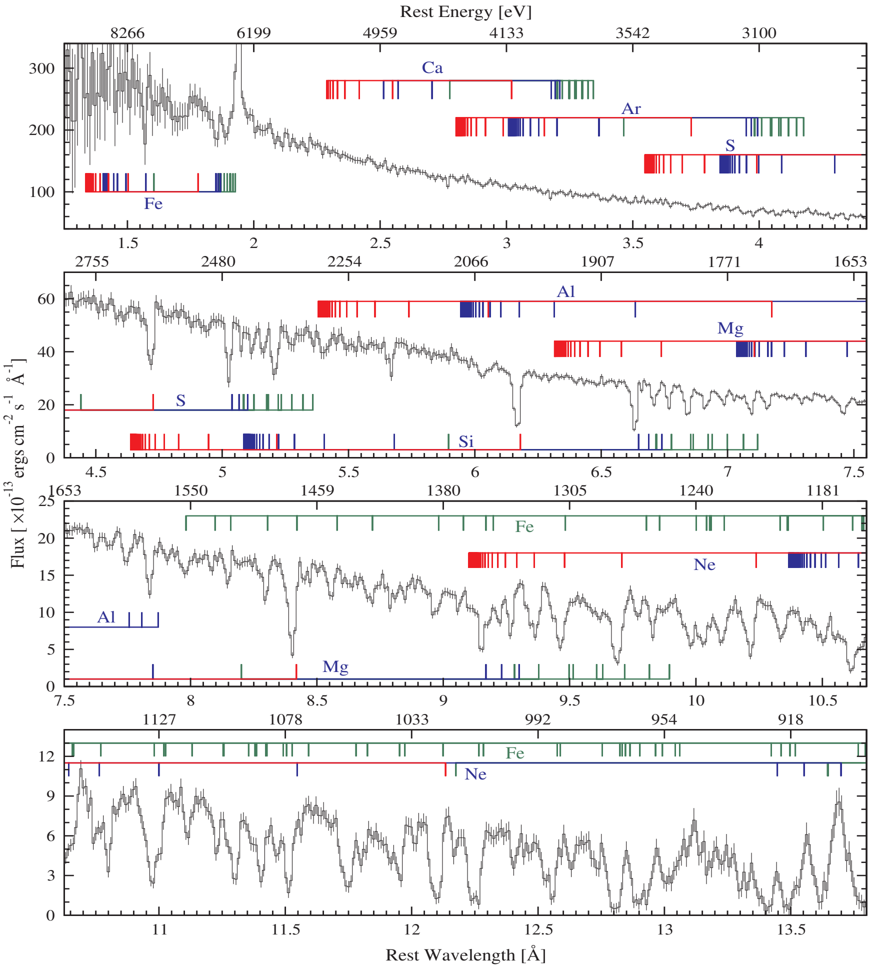


**FIGURE 1.** Part of the 10.4-day *Chandra* HETGS spectrum of the Seyfert galaxy NGC 3783. Marked are the large number of detected absorption lines as well as several emission lines. The lines are marked at their expected wavelengths in the rest frame of NGC 3783; the blueshifts of the absorption lines are noticeable. In total, more than 140 spectral features are detected in the X-ray spectrum of NGC 3783. Adapted from Kaspi et al. (2002).

Stone, & Kallman 2000; Elvis 2000), a dusty torus (e.g., Voit, Weymann, & Korista 1993; Krolik & Kriss 1995), or perhaps stars in the nucleus (e.g., Scoville & Norman 1995; Netzer 1996).

Ionized absorption in the X-ray band has been intensively studied in bright, low-redshift AGN for over a decade (e.g., the "warm absorbers" in Seyfert galaxies; Reynolds 1997; George et al. 1998). The luminous X-ray source in the nucleus acts as a "flash-light" allowing observers to "X-ray" material along the line of sight. However, prior to the launches of *Chandra* and *XMM-Newton*, such investigations were limited by a lack of spectral resolution. Over the past three years, the X-ray grating spectrometers on these

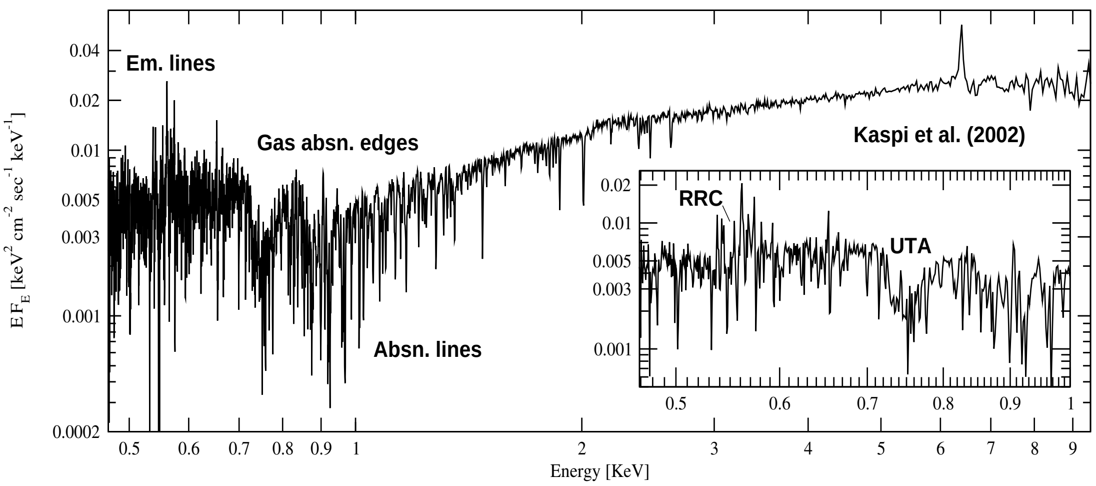


**FIGURE 2.** The 10.4-day *Chandra* HETGS spectrum of the Seyfert galaxy NGC 3783 shown in $EF_{\rm E}$ vs. energy format. The insert focuses on the spectrum below 1 keV. The different types of observed spectral features are labeled. Adapted from Kaspi et al. (2002).

two missions[1] have enlarged the number of spectral features available for study by a factor of $\sim 50$ (see Fig. 1; from 2–3 to more than 140). They have improved the velocity resolution available to observers from $\sim 15,000$ km s$^{-1}$ to $\sim 400$ km s$^{-1}$. They have thereby provided qualitatively new information on the physical conditions, kinematics, and geometry/location of the absorbing material.

At present, efficient grating X-ray spectroscopy is possible only for $\approx 20$ bright, low-redshift (mainly $z < 0.1$) AGN, mainly Seyfert galaxies. Even for these, the required observation lengths are typically $\gtrsim$ 1–2 days; the spectrum of NGC 3783 shown in Fig. 1 required a 10.4-day exposure with *Chandra*. Of necessity, the discussion below applies predominantly to this fairly small sample of objects. Highly luminous and distant quasars, for example, may have significantly different X-ray absorption properties. Furthermore, the discussion below will be closely tied to the X-ray observations, without detailed descriptions of theoretical models. For further information on theoretical models, the reader should consult one of the current reviews (e.g., Netzer 2001; Krolik 2002; and references therein).

## SOME KEY RESULTS FROM X-RAY GRATINGS STUDIES

The spectral features seen in the current X-ray gratings studies include absorption lines [sometimes in unresolved transition arrays (UTAs)], emission lines, absorption edges

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[1] The relevant instruments are the *Chandra* High-Energy Transmission Grating Spectrometer (HETGS; C.R. Canizares et al., in preparation), the *Chandra* Low-Energy Transmission Grating Spectrometer (LETGS; Brinkman et al. 1997), and the *XMM-Newton* Reflection Grating Spectrometer (RGS; den Herder et al. 2001).

(from gas and perhaps dust), and radiative recombination continua (RRCs).[2] The X-ray absorption lines are the most numerous features and are from H-like and He-like ions of C, N, O, Ne, Mg, Al, Si, and S. Inner-shell absorption lines from lower ionization ions, Fe L-shell lines, and Fe M-shell lines are also seen. Fig. 2 illustrates the observed features in the spectrum of NGC 3783. Taken together, these features are sensitive to a wide range of ionization parameter and column density, and they also provide useful temperature and density diagnostics. Furthermore, the ionizing continuum is directly visible (unlike the case for UV absorption lines, where the ionizing continuum is displaced in wavelength), and X-rays are relatively immune to dust extinction effects that can hinder studies at other wavelengths.

## Physical Conditions in Outflows

Gratings observations have clearly established that a uniform, single-component model for the X-ray absorbing material in the outflow is too simple. Outflows contain gas with a wide range of ionization parameter. Fig. 3, for example, shows X-ray absorption lines from the wide range of ions observed in NGC 3783. It is not possible to fit both the low-ionization and high-ionization absorption lines simultaneously with a single "zone" of photoionized gas (e.g., Kaspi et al. 2002; Blustin et al. 2002). Similar results have been found for several other AGN (e.g., Sako et al. 2001; Kaastra et al. 2002). Current models for the outflow usually assume the absorbing gas is in photoionization equilibrium. This is a plausible assumption for some AGN, such as NGC 3783, that exhibit fairly slow and small-amplitude X-ray variability. However, AGN with more rapid and large-amplitude variability (e.g., NGC 4051 and other "Narrow-Line Seyfert 1" galaxies) may contain non-equilibrium X-ray absorbers (e.g., Nicastro et al. 1999; Collinge et al. 2001).

Early photoionization modeling of the ionized absorbers in Seyfert galaxies suggested that they have temperatures $(T)$ of a few $10^5$ K. The gratings data now confirm the expected temperatures. In NGC 3783, for example, modeling of the O VII and N VI RRCs indicate $T \gtrsim 6 \times 10^4$ K, and constraints from He-like triplet emission lines require $T \lesssim 10^6$ K (Kaspi et al. 2002).

Column densities for some of the stronger absorption lines detected from AGN outflows can be estimated via "curve of growth" analyses. However, in such analyses, it is essential to avoid lines that are saturated. The identification of saturated lines can be difficult, since they need not appear "black" (i.e., drop to zero intensity) due to the presence of nuclear X-ray scattering or multiple, unresolved line components (compare Hamann 1998 and Arav et al. 1999). Lines representing transitions to high atomic levels are the least likely to be affected by saturation (due to their lower oscillator strengths), and analyses of such lines indicate O VII and O VIII column densities of a few $10^{18}$ cm$^{-2}$. The corresponding total hydrogen column densities, assuming solar abundances and a reasonable ionization correction, range from a few $10^{21}$ cm$^{-2}$ to $\approx 10^{22}$ cm$^{-2}$. Considering

[2] See the conference papers by E. Behar and T. Kallman for further discussion of some of these features.

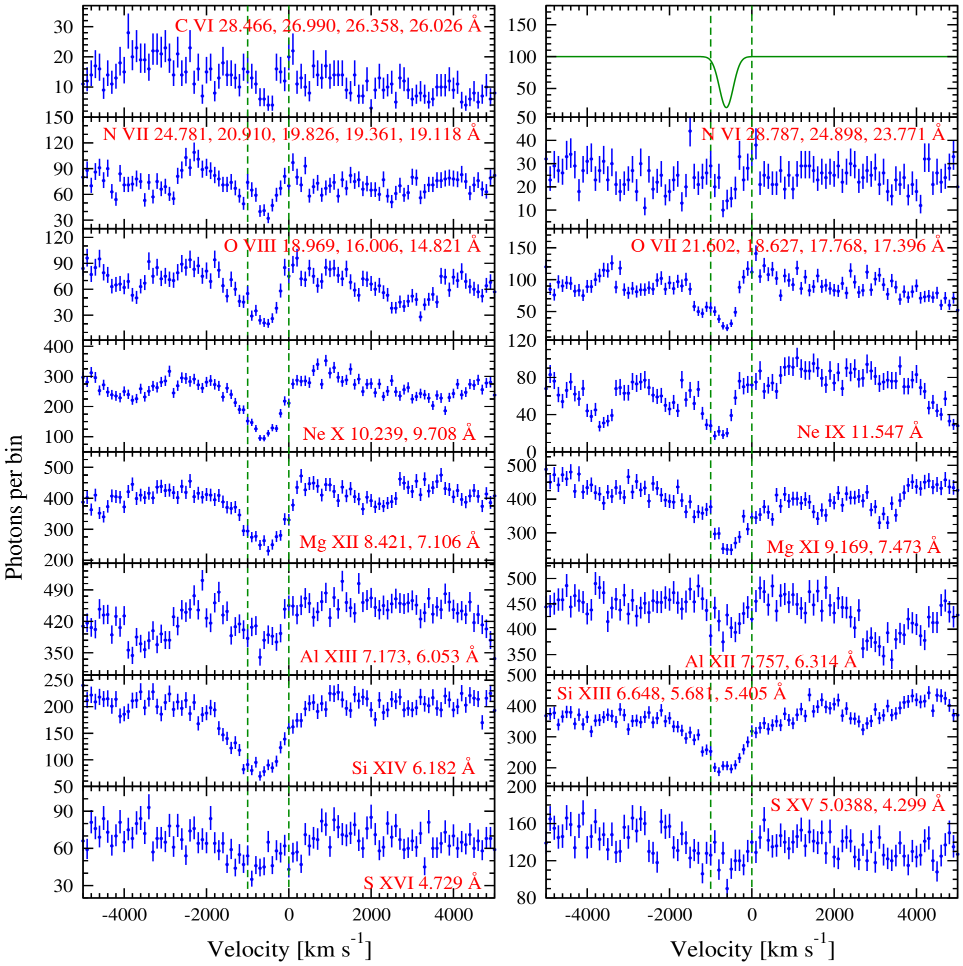


**FIGURE 3.** Velocity spectra showing co-added lines from different ions in the 10.4-day *Chandra* HETGS spectrum of the Seyfert galaxy NGC 3783. H-like ions are shown on the left, and He-like ions are shown on the right. The bin size is 100 km $s^{-1}$, and vertical dashed lines are given at velocities of 0 km $s^{-1}$ and $-1000$ km $s^{-1}$ to guide the eye. In the uppermost right panel we show a Gaussian absorption line representing the line response function of the instrument at 17.396 Å (the FWHM is 397 km $s^{-1}$); this is the poorest line response function applicable to the co-added velocity spectrum of O VII. Note the asymmetry of the O VII lines that is apparently from an additional absorption system. Adapted from Kaspi et al. (2002).

the statistical and systematic uncertainties currently present in curve of growth analyses, solar abundances usually appear consistent with the data. Some AGN outflows may also contain significant column densities of metals in the form of dust grains; X-ray gratings studies offer the exciting possibility of detecting these grains directly and measuring their chemical composition (e.g., Lee et al. 2001).

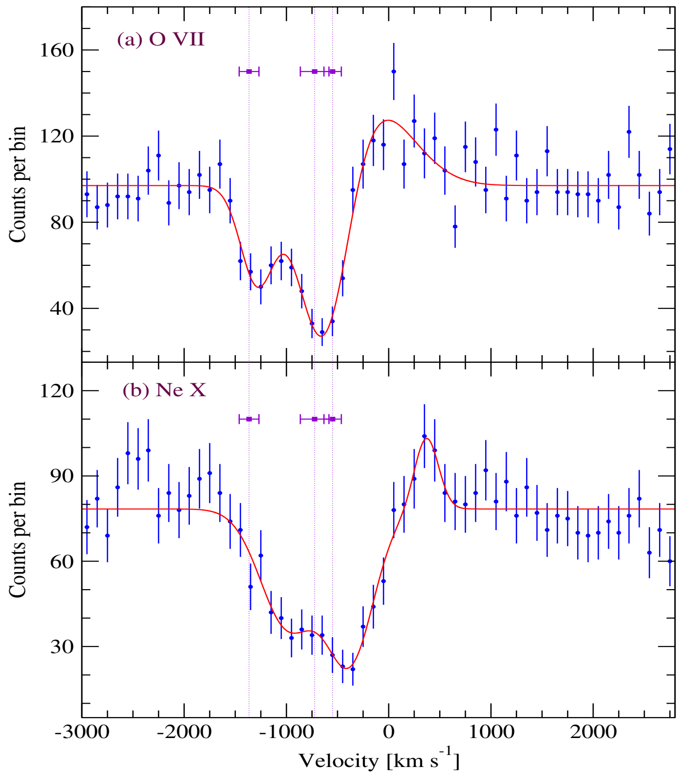


**FIGURE 4.** Velocity spectra, binned at 100 km s$^{-1}$ resolution, of (a) four strong lines of O VII and (b) two strong lines of Ne X in the 10.4-day *Chandra* HETGS spectrum of the Seyfert galaxy NGC 3783. A three-Gaussian fit to each spectrum individually is overplotted on the data points (two Gaussians are in absorption, and one is in emission). Two absorption systems are clearly detected in O VII and probably exist in Ne X as well, although there are statistically significant differences between the O VII and Ne X absorption-line profiles. The vertical lines show the velocity shifts of the observed UV absorption systems; the squares with horizontal error bars show the FWHMs of these systems. Adapted from Kaspi et al. (2002).

## Kinematics of Outflows

The most important, basic result on kinematics from X-ray gratings studies is that the X-ray absorbing gas is generally in a state of outflow with a bulk velocity of a few hundred km s$^{-1}$ (as derived from the blueshifts of X-ray absorption lines). Prior to *Chandra* and *XMM-Newton*, it was not possible to speak reliably about the X-ray absorber as an outflow! In several cases, it has also now been possible to resolve the X-ray absorption lines. X-ray absorbing outflows can have velocity dispersions comparable to their bulk velocities, perhaps due to acceleration of the outflow or turbulence. Furthermore, in a few cases, multiple kinematic components in a single ion have been discovered (e.g., see Fig. 4). As illustrated in Fig. 4 and Fig. 5, different ions can have different kinematic properties; ionization level and kinematics are therefore connected. It is important to note that there may be systematic errors in velocity measurements derived from X-ray absorption lines. For example, some X-ray lines show “P Cygni” profiles where the emission line partially fills the red side of the absorption line. If this (geometry depen-

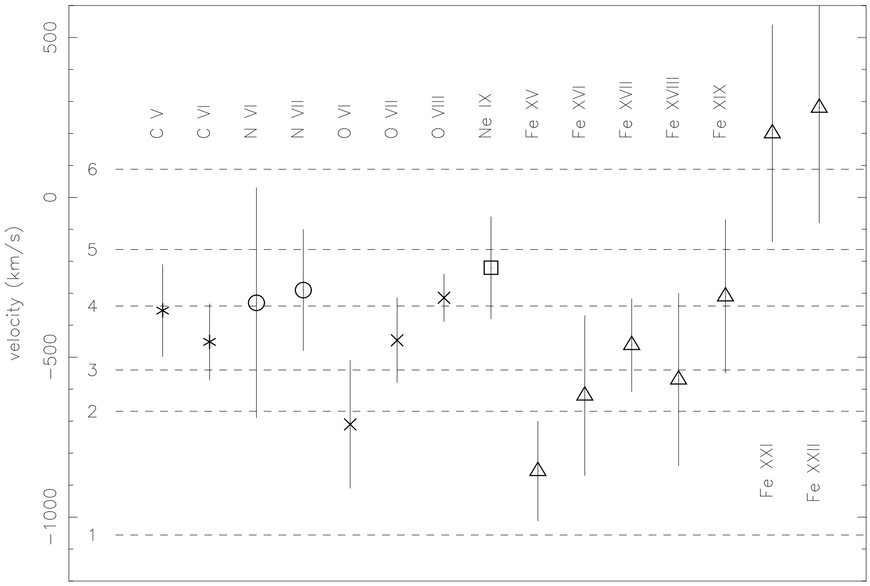


**FIGURE 5.** Average velocities (with respect to the AGN rest frame) for the X-ray absorption lines of different ions in the *Chandra* LETGS spectrum of the Seyfert galaxy NGC 5548. The dashed horizontal lines show the velocities of the six absorption components identified in the UV. Note the tendency for less ionized iron ions to have larger outflow velocities. Adapted from Kaastra et al. (2002).

dent) effect is not properly modeled, velocity measurements can be biased to be too large (because the effective centroid of the fitted absorption line is shifted blueward). This effect appears to be present in the 10.4-day *Chandra* HETGS spectrum of NGC 3783 (Kaspi et al. 2002; although alternative interpretations are possible), and it may well be present but difficult to correct in X-ray gratings spectra with lower signal-to-noise.

The outflow velocities measured from X-ray absorption lines often agree with those measured from UV absorption lines such as C IV, N V, and H I (e.g., see Fig. 4 and Fig. 5), supporting the general existence of a connection between these two types of absorption (e.g., Mathur, Elvis, & Wilkes 1995; Crenshaw et al. 1999). The exact nature of this connection, however, depends upon details of the modeling and remains debated (e.g., Crenshaw & Kraemer 1999; Arav, Korista, & de Kool 2002; and references therein).

## Geometry and Radial Location of Outflows

From the relative strengths of the emission and absorption lines in the AGN with X-ray gratings spectra, the global covering factor of the X-ray absorbing outflow appears to be large.[3] The outflow covers $\gtrsim 50\%$ of the sky that is not already covered by the torus of AGN unification schemes. This direct constraint on the global covering factor agrees

[3] The global covering factor is the fraction of the sky, as seen from the central source, covered by the X-ray absorbing outflow.

well with the indirect constraint derived from counting the fraction of local Seyfert 1 galaxies with ionized X-ray absorbers. The line-of-sight covering factor also appears to be large in at least a few AGN; it can be constrained by measuring the extent to which saturated lines appear black.[4] In NGC 3783, for example, the Fe XX lines near 12.8 Å (see Fig. 1) limit any electron-scattered X-ray contribution to be $\lesssim 15\%$ (Kaspi et al. 2002).

The most important remaining uncertainty about X-ray absorbing outflows is their radial location; this key quantity is not directly constrained by a single observation of an AGN. Possible radial locations range from $\sim 10^{16}$ cm (e.g., an accretion disk wind) to $\sim 10^{18}$ cm (e.g., a torus wind), and there may be absorbing material across this entire range of radii. Knowledge of the radial location is essential for determining the mass outflow rate, the kinetic energy of the outflow, and the overall importance of the outflow in the AGN system. One physically appealing possibility is that the material in the X-ray absorbing outflow is the same material that scatters radiation to the observer in Seyfert 2 galaxies (e.g., Krolik & Kriss 1995; Krolik & Kriss 2001), but this connection cannot be firmly established until the radial location of the X-ray absorbing outflow is known. Variability studies combined with improved density diagnostics may allow the radial location to be determined (e.g., Krolik & Kriss 2001; Netzer et al. 2002), but this will require expensive *Chandra* and *XMM-Newton* observations at multiple epochs.

## POSSIBLE FUTURE DIRECTIONS

### The Need for Better X-ray Spectral Resolution

While the new data from *Chandra* and *XMM-Newton* represent an *enormous* advance, it is likely that X-ray spectroscopy of AGN outflows is still limited in some fundamental ways. One possible problem is illustrated in Fig. 6, where *Chandra*, *HST*, and *IUE* spectra of the Seyfert galaxy NGC 4051 are compared. Given the results from UV observations, it appears at least plausible that the ionized X-ray absorbers in AGN have significant velocity structure that cannot be resolved with current X-ray instruments. The velocity structure currently apparent in the X-ray spectra (e.g., Fig. 4 and Fig. 5) may just be the "tip of the iceberg." An optimist might argue that the high-temperature X-ray absorbing material will tend to be more volume filling than the lower temperature UV absorbing material, and therefore that it will be less clumpy. However, *FUSE* spectra of lines from the high-ionization ion O VI still show velocity structure finer than can be resolved with current X-ray instruments (e.g., Gabel et al. 2002).

If the X-ray absorption lines indeed possess significant unresolved structure, this will lead to systematic errors when attempting to derive column densities, ionization levels, and other physical parameters. Some line components may be saturated even though the unresolved average "line" does not appear black. A velocity resolution of $\sim 100$ km s$^{-1}$

[4] The line-of-sight covering factor is the fraction of the line-of-sight to the central source covered by the X-ray absorbing outflow. In reality, there may be multiple lines of sight to the central source if it has physical extent or if X-ray scattering is present.

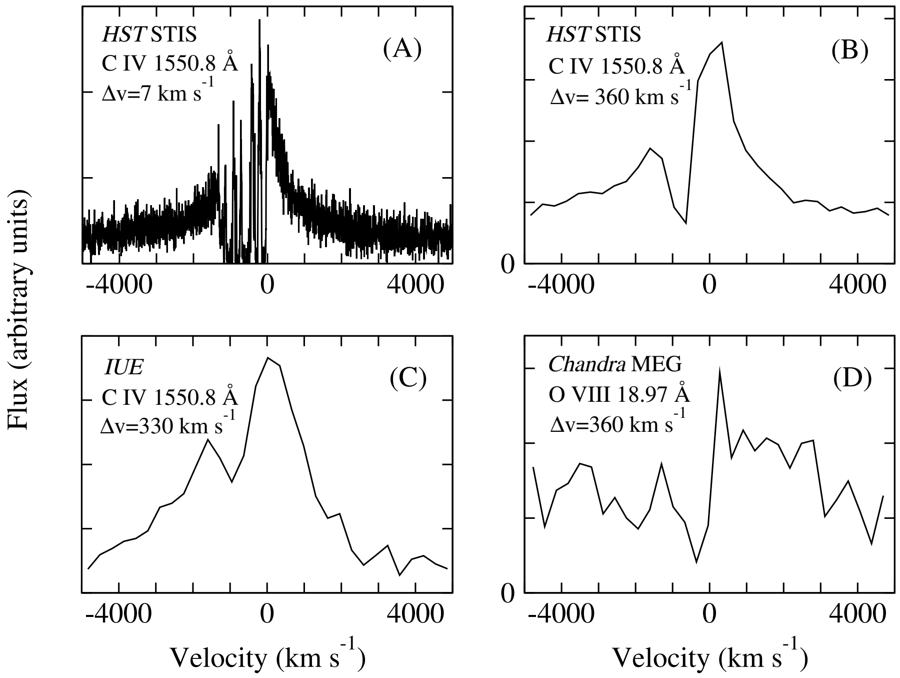


**FIGURE 6.** UV and X-ray absorption systems in the Seyfert galaxy NGC 4051 as seen by the *HST* Space Telescope Imaging Spectrograph (STIS; a and b), *IUE* (c; mean of 1978–1988 and 1994 epochs), and the *Chandra* HETGS (d; the MEG is part of the HETGS). The *Chandra* and *HST* observations were performed simultaneously in 2000. The approximate velocity resolution is listed for each panel. Panel (b) represents the STIS C IV line binned to the velocity resolution of the HETGS. Comparison of the panels stresses the point that the ionized X-ray absorber may be subdivided into further systems that cannot be resolved with current X-ray instruments. Note the similarity between panels (b) and (d), even though the high resolution in panel (a) reveals the C IV absorption to be extremely complex with at least eight distinct kinematic components. Adapted from Collinge et al. (2001).

or better will probably be required to resolve the X-ray lines. Such a resolution would also be valuable for addressing numerous other astrophysical issues (e.g., Elvis 2001). To our knowledge, no X-ray missions with the requisite resolution are currently scheduled for launch.

## The Need for Higher Throughput

As mentioned above, efficient grating X-ray spectroscopy is presently possible only for $\approx 20$ bright, low-redshift (mainly $z < 0.1$) AGN. Photon starvation has limited our ability to perform grating X-ray spectroscopy of more luminous but more distant AGN, such as BALQSOs. This is unfortunate, since the outflows in these objects are faster and probably more powerful than those in local AGN (e.g., see Laor & Brandt 2002 and references therein). The current X-ray spectra of BALQSOs, obtained with Charged Coupled Device (CCD) detectors, show that heavy X-ray absorption is often present (e.g., Green et al. 2001; Gallagher et al. 2002). In most cases, however, the dynamical state of the X-ray absorbing gas is unknown. One notable exception appears to be the

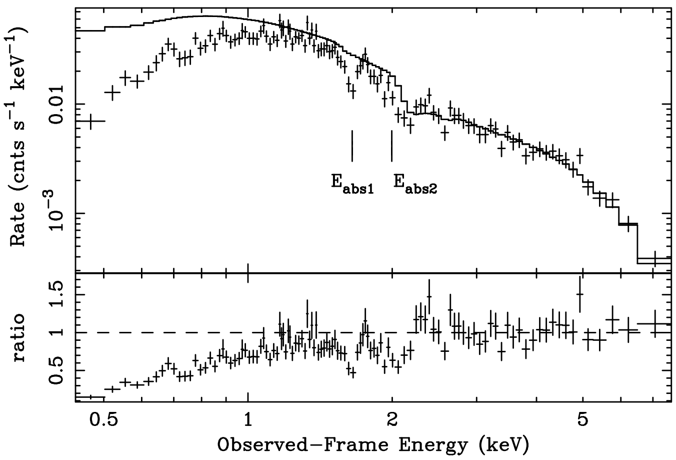


**FIGURE 7.** The observed-frame *Chandra* spectrum of the $z = 3.91$ BALQSO APM 08279+5255. The spectrum has been fit above 2.2 keV (10.8 keV in the rest frame) with a power-law plus Galactic absorption model; the model has then been extrapolated to lower energies to show the residuals. The lower panel shows the ratio of the data to the model. Note the absorption at low energies as well as the two apparent absorption lines from 1.5–2.1 keV. Adapted from Chartas et al. (2002).

gravitationally lensed BALQSO APM 08279+5255 at $z = 3.91$. Chartas et al. (2002) have recently claimed the detection of X-ray BALs from iron K$\alpha$ that imply outflow velocities of $\approx$ (0.2–0.4)$c$ (Fig. 7; also see Hasinger, Schartel, & Komossa 2002 for additional X-ray observations and an alternative interpretation).

High-throughput spectroscopy with enough resolution to determine the velocities of the X-ray absorbers in BALQSOs should provide a qualitative advance in our understanding of BALQSO outflows. Without basic kinematic information on the X-ray absorber, it is impossible to determine the total mass outflow rate and the kinetic energy of the outflow. Extremely high spectral resolution is probably not required for this science due to the high velocities observed in the UV; a velocity resolution of $\sim 1000$ km s$^{-1}$ should be sufficient to allow major progress. Long *XMM-Newton* observations of 1–3 of the X-ray brightest BALQSOs can provide crucial information, but missions such as *Constellation-X* and *XEUS* will be needed to make high-resolution X-ray spectroscopy of BALQSOs routine.

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