Observable Properties of X-ray Heated Winds in AGN: Warm Reflectors and Warm Absorbers

Julian H. Krolik

and

Gerard A. Kriss

Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218

ABSTRACT

First discovered by spectropolarimetry, the warm reflecting gas near active galactic nuclei may be observed in many ways. When the nucleus itself is obscured, and instrumental angular resolution is fine enough to exclude radiation from the host galaxy, this gas can be seen in the soft X-ray band by a combination of bremsstrahlung, intrinsic line emission, and reflection of the nuclear continuum, both by electron scattering and by resonance line scattering. Strong blended line features can be expected in the spectrum. We show that the strong emission line features seen in the keV region in the X-ray spectra of obscured AGN may be due to this gas, partly due to intrinsic emission (as suggested by some previous studies), and partly due to resonance scattering. In the ultraviolet, intrinsic emission is very weak, and strongly dominated by lines. Reflection, principally by electron scattering, but also with some contribution from resonance lines, is the main signature in the UV.

When our line of sight to the nucleus is not obscured, the dominant effect is absorption. In the soft X-ray band, ionization edges of highly ionized species and resonance lines contribute comparably to the opacity; in the ultraviolet, the gas is almost transparent except for a small number of resonance lines.

We identify the “warm absorbers” seen in many AGN X-ray spectra with this gas, but argue that most of the UV absorption lines seen must be due to a small amount of more weakly ionized gas which is embedded in the main body of the warm, reflecting gas. Because the ionization equilibration timescales of some ions may be as long as the variability timescales in AGN, the ionic abundances indicated by the transmission spectra may not be well-described by ionization equilibrium.

1. Introduction

The first strong evidence that significant quantities of warm ($T \sim 10^6$K) gas could be found near active galactic nuclei came from the spectropolarimetry of Antonucci & Miller (1985). In that
work they found that the optical polarization spectrum of the archetypical type 2 Seyfert galaxy, NGC 1068, could only be explained if our line of sight to its nucleus were obscured, and a small fraction of the nuclear continuum were reflected to us by electron scattering in warm, ionized gas concentrated along the axis of the nuclear radio jet. Miller & Goodrich (1990), Tran, Miller, & Kay (1992), and Kay (1994) later found similar behavior in many other type 2 Seyfert galaxies, and analogous regions of warm electron scattering gas have been suggested in radio galaxies as well (Barthel 1989; Antonucci & Barvainis 1990; Antonucci, Hurt, & Kinney 1994).

On the basis of optical/ultraviolet spectropolarimetry and imaging, it has been possible to roughly estimate the physical conditions of this gas. In NGC 1068, comparing the polarized line widths seen in a dust reflection nebula distant from the nucleus to the polarized line widths seen in the nuclear reflection region yields a temperature \( T \approx 3 \times 10^5 \) K and a Thomson optical depth \( \tau_T \sim 0.1 - 0.01 \) (Antonucci & Miller 1985; Miller, Goodrich, & Mathews 1991). HST imaging indicates a characteristic dimension for the warm reflecting gas in this galaxy of \( \sim 10 - 100 \) pc (Kriss et al. 1993; Capetti et al. 1994). Consequently, the ionization parameter \( \Xi \) (defined as \( J_{\text{ion}}/(cp) \), where \( p \) is the total gas pressure) is \( \sim 25L_{45}[(\tau_T/0.01) (r/30 \text{ pc}) (T/3 \times 10^5 \text{ K})]^{-1} \) (Krolik & Begelman 1986). Here we have scaled to the luminosity estimated for NGC 1068 by Pier et al. (1994). If the ionizing spectrum of NGC 1068 is similar to those (Figure 1) of typical unobscured AGN (as Pier et al. 1994 found), this ionization parameter and temperature indicate (Figure 2) that in net, the gas absorbs more heat from the continuum than it radiates, but it is not far from equilibrium (cf. the somewhat idiosyncratic spectrum suggested by Marshall et al. 1993, for which this gas might actually find itself in radiative equilibrium if the ionization parameter lies within a special narrow range of values). This placement in the \( (T, \Xi) \) plane suggests an origin for the gas in recent ionizing evaporation from cooler gas, as the dynamics of this process tend to lock the ionization parameter to values slightly in excess of critical (Krolik, McKee, & Tarter 1981; Krolik & Begelman 1986). Net radiative heating drives the gas outward at mildly supersonic speeds. That this description is at least qualitatively correct is supported by the fact that this picture predicts (to within factors of a few) the correct temperature and optical depth of the reflecting gas (Krolik & Begelman 1986; Balsara & Krolik 1993).

A few other observable signatures of this gas have been proposed, and, in some cases, detected. Krolik & Kallman (1987) predicted that type 2 Seyfert galaxies with thick enough obscuration to block the 6 keV band should display Fe K\( \alpha \) lines of large (\( \sim 1 \) keV) equivalent width and energies corresponding to rather high ionization stages. These have, indeed, been seen in several cases (Koyama et al. 1989; Marshall et al. 1993; Awaki et al. 1990; Awaki et al. 1991; Ueno et al. 1994). Band et al. (1990) showed that resonance scattering of the K\( \alpha \) line could also contribute to the observed feature. Krolik & Kallman (op. cit.) also predicted that type 1 Seyfert galaxies should show highly ionized Fe K photoionization edges with optical depths \( \sim 0.1 \), and possibly OVIII ionization edges.

It is the goal of this paper to predict a number of new observational signatures of this gas, to make more quantitative the old predictions of X-ray absorption features, and to compare these
predictions to extant observations. In order of discussion, these signatures are: the intrinsic emission spectrum; scattering; and absorption. We concentrate on the UV and X-ray bands because most of the intrinsic emission comes out in the range $0.1 - 10$ keV and the strongest line features under the conditions of interest are in the soft X-ray band. In addition, emission by stars in the host galaxy is relatively weaker in these bands, and therefore easier to exclude.

The work we present differs in a number of important respects from earlier work on the X-ray irradiation of gas near Seyfert nuclei. First, the range of physical conditions we study is determined by dynamical models; in some previous efforts (e.g. Netzer 1993), the gas was assumed to be strongly clumped, despite the absence of a confinement mechanism, and the range of ionization states given the most attention is thermally unstable for many common AGN spectral shapes. Second, we find that the scattering opacity due to resonance lines can be very significant, and that a very large number of lines from many different ions contribute ($\S$4,5); in this context only Band et al. (1990) had previously recognized this effect of resonance lines, but they only considered the Fe K$\alpha$ line. Third, in all previous papers on this subject, the gas was assumed to be in ionization balance (e.g. Turner et al. 1993), and in many it was assumed to be in thermal balance as well (e.g. Yaqoob & Warwick 1991; Netzer 1993; Fabian et al. 1994); as we show here ($\S$2,6) both of these assumptions are questionable.

2. Calculational Method

Each of the properties we wish to predict depends on both $T$ and $\Xi$, scaled by either an emission measure or the column density. Our procedure will be to use the photoionization code XSTAR (Kallman & Krolik 1993) to compute models at four representative points in $(T, \Xi)$ space: $(T = 3 \times 10^5 \text{ K}, 10^6 \text{ K}) \times (\Xi = 10, 100)$, and scale the results appropriately. Given the estimates of the previous section, this box should span most of the likely range of conditions for this gas.

Details about the operation of XSTAR may be obtained, as is explained in Kallman & Krolik (1993), by anonymous ftp from legacy.gsfc.nasa.gov. This code is particularly appropriate for this problem because of its extensive X-ray line list, some 665 lines at energies above 120 eV. In this application, we use XSTAR to compute the ionization balance in and intrinsic emission from a succession of zones within a slab of fixed column density. These zones are chosen to be sufficiently thin that the continuum radiation transfer is well-described, although this is not much of an issue for our models because they are optically thin in most continuum bands. Three passes through the slab are made so as to converge on the correct line and continuum optical depths from each zone to either side. Emergent flux is corrected for any absorptive opacity; when we cite intrinsic emission, we give the total emission through both sides of the slab. Total line and continuum optical depths through the slab are a byproduct of this calculation.

All our models are computed with the same spectrum, designed to be representative of
those seen in typical type 1 Seyfert galaxies and low-luminosity quasars (see Figure 1). We also consistently assume solar abundances. Since these lower luminosity AGN have higher X-ray to optical luminosity ratios than the typical quasar, our ionizing spectrum is considerably harder than that of Mathews & Ferland (1987). We chose our spectral shape to be the same as theirs at wavelengths longward of 2500 Å, but at shorter wavelengths we use a power law of index 1.0 extending into the extreme UV. This is a little flatter than slopes for Seyfert 1’s and 2’s (e.g., Kinney et al. 1991), but corrects for steepening due to Fe II and Balmer continuum emission, and it matches the low luminosity QSO slope of 1.0 from O’Brien, Gondhalekar, & Wilson (1988). The observed hard X-ray spectrum of Seyferts is a sum of intrinsic emission and a Compton-reflected hard tail. We assume both components illuminate the gas and use an energy index of 0.75 from 0.5 keV to 100 keV. This matches the observed mean for Seyferts (Nandra & Pounds 1994). At 100 keV our spectrum breaks to an index of 2.4 to match the OSSE spectrum of NGC 4151 (Maisack et al. 1993). The X-ray normalization relative to the UV is determined assuming \( \alpha_{\text{ox}} = 1.25 \), appropriate for Seyferts and low-luminosity quasars (Kriss & Canizares 1985). The low energy X-ray spectrum steepens to an index of 2.0 below 0.5 keV. Soft X-ray excesses in AGN span a large range of break point energies and effective spectral indices, but our chosen values are near the middle of the range observed by Walter et al. (1994). This steep low energy X-ray spectrum meets the UV power law at a breakpoint of 78.91 eV.

Figure 2 shows the radiative equilibrium curve for this spectrum. The four points we have chosen span the region expected on the basis of both empirical and theoretical arguments. Examining models in ionization equilibrium but out of radiative equilibrium is physically justified on the basis of the following timescale ratios:

\[
\frac{t_{\text{recomb}}}{t_{\text{flow}}} \simeq 5 \times 10^{-4} \left( \frac{\tau_T}{0.01} \right)^{-1} T_6^{1.2} M^1
\]

\[
\frac{t_{\text{heat}}}{t_{\text{flow}}} \simeq 0.5 \left( \frac{\tau_T}{0.01} \right)^{-1} T_6^{1.5} M,
\]

where the recombination time has been evaluated for OVIII assuming that the abundances of OVIII and OIX are equal, and the heating time has used the net rate, \( i.e. \) after subtracting off radiative cooling. This latter point is significant because the most likely regime is one in which the net heating minus cooling is \( \sim 0.1 \times \) the full heating rate. For this reason, particularly when the Mach number \( \mathcal{M} \simeq \text{few} \), adiabatic cooling can be significant, and the flow time can be comparable to the time required for relaxation to radiative equilibrium.

The arguments of the preceding section demonstrate that ionization balance should be a good approximation, despite the dynamical changes in wind density and temperature, if the ionizing flux is constant. However, AGN are known to vary. In §6 we will discuss the effects due to a variable ionizing flux.

3. Intrinsic Emission
All the processes by which gas in these conditions radiates—bremsstrahlung, radiative recombination, and collisional excitation—scale with density squared, so the most direct way of describing the radiative output is in terms of an effective spectral cooling function $\Lambda_\nu$, which is a function of $\Xi$ and $T$, and an emission measure. Note that in our regime, no strong line is affected by collisional deexcitation, so there is negligible separate dependence on the absolute density.

The approximation of choosing a single value of $\Xi$ and $T$ amounts to saying that the pressure scales simply as $r^{-2}$ everywhere and the temperature is uniform. Such simplicity is, of course, highly unlikely, and is not found in hydrodynamic simulations (Balsara & Krolik 1993, 1994). However, this approximation may be adequate for our present purposes.

Suppose that this gas expands outward with constant velocity and fixed opening angle. When that is the case, the density varies as $n = n_o(r/r_o)^{-2}$; thus the emission measure outside radius $r_o$ is

$$EM = \int_{r_o}^{\infty} dr \Delta \Omega r^2 n_o^2 (r/r_o)^{-4}$$

$$= \Delta \Omega n_o^2 r_o^3,$$

where $\Delta \Omega$ is the solid angle of its expansion cone. Note that 3/4 of the total is accumulated within $2r_o$. In the case of warm reflecting gas in AGN, it is most useful to take $r_o$ as the radius at which the gas expands out over the surrounding obscuration. Gas closer in is, of course, only partially visible when the nucleus itself is obscured.

Following Krolik & Begelman (1986), we expect the temperature at $r_o$ to be

$$kT_o \simeq (3\mu/5)^{1/3} \left( \frac{L \sigma_{eff}}{3\pi r_o} \right)^{2/3}$$

where the mean mass per particle is $\mu$, and $\sigma_{eff}$ is the absorption cross section appropriately averaged over frequencies. Because the heating rate is $\propto r^{-2}$, while the adiabatic cooling rate is $\propto r^{-1}$, if the velocity is constant we expect the temperature outside $r_o$ to fall roughly as

$$T(r) = T_o \frac{r_o}{r} \left[ 1 + \log(r/r_o) \right].$$

By $r = 2r_o$, the temperature falls by only $\simeq 15\%$. Similarly, the ionization parameter (before allowance for continuum opacity) then varies as

$$\Xi(r) = \Xi(r_o) \frac{r/r_o}{1 + \log(r/r_o)}$$

which likewise changes by only $\simeq 15\%$ from $r_o$ to $2r_o$. Therefore, most of the emission measure is accumulated under conditions of essentially constant (unattenuated) $\Xi$ and $T$, and the approximation of taking a single value for each of these quantities should be a reasonable one.

The emission measure may also be rewritten in terms of quantities more closely tied to observations. It is

$$EM = C \frac{\Delta \Omega L_{ion} T}{4\pi c \sigma_T kT \Xi(n_e/n_H + n_i/n_H)},$$
where $C \equiv \langle n^2 \rangle / \langle n \rangle^2$ is an allowance for the possible effects of clumping. Thus, if $T$ and $\Xi$ are relatively uniform over the entire sample of AGN, the emission measure for any particular object, and hence the total intrinsic X-ray flux, scales $\propto L \tau T \Delta \Omega$. On the other hand, increasing $T$ and $\Xi$ decreases the emission measure.

### 3.1. Soft X-rays

Results from XSTAR calculations are presented in Figs. 3. All have $\tau T = 0.0665$ (corresponding to $N_e = 10^{23} \text{cm}^{-2}$). The normalizations assume that the irradiating continuum has a luminosity of $10^{44}$ erg s$^{-1}$ in photons more energetic than 13.6 eV, and that $C \Delta \Omega = \pi$. Solid curves show the total emission from lines and continua smoothed by a Gaussian of constant fractional width $\Delta \nu / \nu = 0.05$. The dotted curves show the bremsstrahlung and recombination continua alone, with no smoothing.

As is obvious from these figures, the soft X-ray emission is very strongly line-dominated, even for the higher values of $\Xi$. OVIII Ly$\alpha$ is always strong, but a number of other lines are often comparable. We confirm the suggestion of Band et al. (1990) that the Fe L recombination lines clustered near 1 keV are also strong. If it were only for bremsstrahlung, the emission would be 1 – 3 orders of magnitude weaker, depending on the model and the energy at which the comparison is made. When the spectra are smoothed by finite resolution, the lines blend into a pseudo-continuum, but the strongest lines and line blends still stand out. Note also that in a few places the net emitted spectrum actually lies below the spectrum due to continuum processes alone; this is an artifact of the smoothing we imposed on the total spectrum but not on the pure continuum spectrum.

Figures 3 also show that the emission measure scaling predicted by equation 8 is borne out: in crude terms, $L_x \propto (T \Xi)^{-1}$. However, the complicated spectral shape means that the actual X-ray luminosity measured by any particular instrument will depend strongly on the specific energy-dependent sensitivity of that instrument. Although the emission is weak compared to the nuclear luminosity (by a factor of $\sim 10^{-3\pm1}$), it is not necessarily negligible. When our line of sight to the nucleus is blocked, the emission from this gas should often be quite noticeable (see §7.2).

Several factors contribute to the weakness of the intrinsic emission: the gas in these conditions is generally rather optically thin, so that only a small fraction of the incident continuum energy heats the gas; particularly in models c and d total heating exceeds total cooling; and we normalize to a condition in which the gas covers only 1/4 of solid angle around the source.

In general terms, the spectrum above 1 keV can be expected to be quite steep, but (as predicted by Krolik & Kallman 1987), there is a very strong ionized Fe K$\alpha$ emission line. Below 1 keV, the spectrum is flatter, particularly for large $\Xi$ (models c and d). The spectra predicted by Netzer (1993) are significantly steeper than ours below 1 keV, probably because his temperatures
are significantly lower than any of those we consider ($T = 1.3 \times 10^5$ K for his $U = 3$ case). Just as for the total luminosity, the spectral slope measured by any particular instrument will depend strongly on details of its energy-dependent sensitivity because the lines are so strong. Therefore, to test a given model it is essential to fold the predictions of that model through the response matrix for the experiment before making any statements about whether it does or does not match the observed shape.

### 3.2. Ultraviolet

Unless $C \gg 1$, the intrinsic emission of this gas in the ultraviolet is very weak compared to the incident luminosity. The continuum luminosity, which is generated exclusively by bremsstrahlung, follows immediately from the previously estimated emission measure:

$$\frac{\nu L_{\nu}}{L_{\text{ion}}} = 2 \times 10^{-4} \nu_{15} C \frac{\Delta \Omega}{\pi} \frac{\tau T}{0.0665} T_6^{-3/2} \Xi^{-1},$$

where $\nu_{15}$ is the frequency in units of $10^{15}$ Hz. The scaling factors are likely to decrease this ratio still further. Line emission, particularly H and He recombination lines, accounts for a larger luminosity. For example, considering only the H recombination lines, we find

$$\frac{L(\text{Ly} \alpha)}{L_{\text{ion}}} = 3.6 \times 10^{-3} C \frac{\Delta \Omega}{\pi} \frac{\tau T}{0.0665} T_6^{-1.7} \Xi^{-1}. $$

Other, collisionally excited lines, can also be strong, but their emissivities depend in more complicated ways on $T$ and $\Xi$.

Although we expect intrinsic emission in the ultraviolet to be weak in most instances, for the sake of completeness, and for use in the event of large $C$, we present the actual spectral shapes in Figures 4. In addition to the intrinsic weakness of this emission, in practice it will be very difficult to distinguish from narrow line emission (which should be much stronger) unless an extremely small aperture is used. Note also that the Lyman edge emission jump decreases in strength as the temperature increases, but should be easily observable up to temperatures close to $1 \times 10^6$K.

### 4. Scattering

The contribution to the flux from reflection of the nuclear continuum should always be comparable to or greater than the intrinsic radiation. To see this, consider the ratio of the two
specific luminosities, allowing only for the Thomson scattering portion of the reflection:

$$\frac{L_{\nu,\text{intr}}}{L_{\nu,\text{refl}}} = \frac{C \Lambda_{\nu}(T, \Xi) \Delta \Omega L_{\text{ion}} \tau_T/(4\pi c \sigma_T kT \Xi)}{(\Delta \Omega/4\pi) \tau_T L_{\nu,\text{nucl}}},$$

(11)

$$= \frac{C \nu \Lambda_{\nu}(T, \Xi) L_{\text{ion}}}{ckT \sigma_T \Xi \nu L_{\nu,\text{nucl}}}$$

(12)

$$\simeq 8.3C \frac{\nu \Lambda_{\nu}}{\Xi T_6 10^{-23} \text{erg cm}^3 \text{s}^{-1} \nu L_{\nu,\text{nucl}}}.$$  

(13)

In all four of the models considered here, $\nu \Lambda_{\nu}$ in the soft X-ray band is in fact within a factor of two of $10^{-23}$ erg cm$^{-3}$ s$^{-1}$. For $T_6 \lesssim 1$ and $\Xi \sim 10 – 100$, it is clear that the intrinsic soft X-ray emission and reflection by Thomson scattering are comparable. In the ultraviolet, reflection should completely dominate intrinsic emission (unless the clumping factor is quite large) because most of the cooling radiation from gas in this state emerges in the soft X-ray band.

Thomson scattering is not the only sort of scattering significant in this situation, although that assumption has frequently been made in cognate work (e.g. Netzer 1993). As first suggested for the Fe K$\alpha$ line alone by Band et al. (1990), resonance line scattering can substantially enhance the scattering opacity. Our calculations show that so many lines have the potential to be optically thick in these conditions that taken together they can increase the frequency-averaged scattering depth by factors of a few. Details such as exactly which lines participate, and how large their optical depths are, obviously vary with $T$ and $\Xi$.

However, there is another important consideration which renders any quantitative prediction of resonance line scattering rather model-dependent: the strong velocity gradients which are likely to exist. If this warm gas is a pressure-driven wind, as suggested by Krolik & Begelman (1986), then we can expect its mean speed in the region we see to be a few times the sound speed. We can also expect that the geometrical divergence of the wind convolved with velocity gradients parallel to streamlines will introduce velocity differences across the wind of magnitude comparable to the typical wind speed. Because X-ray lines all arise in elements with $Z \sim O(10)$, the local thermal width of atomic speeds is at least an order of magnitude smaller than the actual velocity differences across the wind. Therefore, the equivalent width of an optically thick line is very sensitive to the velocity differences across the wind, which we do not know to anything better than order of magnitude accuracy.

In order to illustrate in at least a tentative way how lines may alter the reflecting properties of this gas, we have computed the reflected fraction under the assumption that the true velocity distribution of the gas is $\propto \exp[-(v/c_s)^2]$, where $c_s$ is the sound speed. While probably not literally correct for any plausible dynamical model, this form for the distribution does at least possess the desirable qualitative properties of being peaked at the center and having a width comparable to the sound speed. We also assume, as we did for our prediction of the intrinsic emission, that the covering fraction is 1/4.

As discussed in §5, there are wavelengths for which this gas can have modest continuum
optical depth. We account for this in the reflected fraction by making the approximation that the mean pathlength for reflected photons is equal to the pathlength for photons travelling straight outward through the gas, and multiplying by the appropriate \( \exp(-\tau) \). In more weakly ionized gas, continuum opacity has a stronger effect on the reflected spectrum (Netzer 1993); here, however, it has only minor impact.

The results for the soft X-ray band are shown in Figures 5. While there are line-free portions of this band, it is clear that on average resonance scattering can increase the reflected fraction by factors of a few relative to the Thomson-only reflected fraction (which for these numbers is 0.0166). The energy range from 1 – 1.5 keV is particularly rich in such lines. As predicted by Band et al. (1990), resonance scattering does significantly enhance the strength of Fe K\( \alpha \) in the reflected spectrum, but this is also true of many other lines, and, as we have already emphasized, the amount of enhancement depends very strongly on the velocity structure of the gas. It is also important to observe that when the gas is relatively weakly ionized (Model b), absorption can actually cause the reflected fraction to fall below the Thomson value.

Figures 6, in which we combine reflected and intrinsic emission from 0.1 to 10 keV, show the actual spectrum that might be observed when the nucleus itself is obscured. Both the intrinsic and reflected contributions scale \( \propto \Delta\Omega\tau_T \); as before, we take \( C\Delta\Omega = \pi \), and \( \tau_T = 0.0665 \). The addition of reflected nuclear continuum to the intrinsic emission has several consequences for the observed spectrum. First, of course, the total flux is increased by a factor of a few. Second, the equivalent widths of emission lines which are either forbidden or arise from excited states are diluted, while the equivalent widths of permitted resonance lines are enhanced. Third, the spectral shape is altered, but in a sense which could vary substantially from object to object because Type 1 Seyfert galaxies, in which we can see the nuclear soft X-ray flux unobscured, show a wide dispersion in soft X-ray spectral slopes (Turner & Pounds 1989; Walter & Fink 1993; Walter et al. 1994). For the purposes of this example, we use the same shape spectrum (Figure 1) that we used for the photoionization calculations.

Although details of the reflected plus intrinsic spectrum depend on the choice of \( \Xi \) and \( T \), one feature is comparatively stable: the large equivalent width Fe K\( \alpha \) line (Krolik & Kallman 1987; Band et al. 1990). As noted by Band et al. (1990) this feature can contain a substantial contribution from resonance scattering in addition to the intrinsic emission. Depending on \( T \) and \( \Xi \), the reflected luminosity in the Fe K\( \alpha \) feature relative to the intrinsic emission of the gas in our models varies from roughly a tenth to of order unity. Another prominent feature is the \( \text{Ly}\alpha \) transition of OVIII. This depends rather more on physical conditions, but it remains strong over most of the expected range.

Before leaving the subject of the observed X-ray spectrum in obscured cases, it is also important to point out that the observed range of column density in the obscuring material is fairly broad: from as little as \( \sim \text{few } \times \text{10}^{22} \text{ cm}^{-2} \) up to \( \text{>10}^{24} \text{ cm}^{-2} \) (Mulchaey et al. 1993). When the Thomson optical depth is at least a few, the nuclear flux is sufficiently suppressed that
the observed spectrum (below 10 keV) should be fairly close to the examples shown in Figures 6. There is a small “Compton reflection” contribution from X-rays scattered off the inner edge of the obscuration, but this is weak except in rather special geometries and for viewing angles nearly out of the obscured range (Krolik et al. 1994; Ghisellini et al. 1994).

However, when the column density is smaller, the nuclear flux can shine through at energies above several keV. In that case, Figures 6 should give a good representation of the X-ray spectrum at lower energies, but above the point where the obscuration becomes optically thin (somewhere between a few and 10 keV), the spectrum will rise steeply and then resume the usual power-law behavior at higher energies (Krolik et al. 1994; Ghisellini et al. 1994). This steep rise also includes a contribution from “Compton reflection” off the inner edge of the obscuration, but its magnitude is, of course, small when the Thomson optical depth of the obscuration is small.

In the ultraviolet, very few lines are optically thick even in the limit of zero velocity gradient. By far the most important are the H Lyman series and the resonance doublets of the Li isoelectronic sequence (see Table 1). Lyα has a significant optical depth in all four models, but only in the most weakly ionized model (Model b) do any others become optically thick, and then it is only the two lines NV λ1240 and OVI λ1034. Nonetheless, resonance lines can produce emission features in the reflection spectrum even when optically thin if their optical depths are greater than the continuum optical depth. In favorable circumstances, therefore, the equivalent width of Lyα, or possibly OVI λ1034, in the reflection spectrum might be as large as \( \sim \lambda (v/c) / \tau_T \sim 100 \AA \). The other lines should, in general, be rather weaker.

Detection of these weak UV reflection features is made even more difficult by the fact that they are superposed on other emission lines. In total flux spectra (unless extremely small apertures are used) they are hidden by narrow line emission; in polarized flux spectra—which eliminate the narrow lines—they are blended with the reflected broad emission lines.

5. Absorption

The transmission fraction follows directly from these same models. It is simply

\[
f_\nu = \exp[-\tau_c(\nu) + \tau_l(\nu)] + f_{\text{refl}}(\nu)
\]

where \( \tau_c(\nu) \) is the continuum optical depth at frequency \( \nu \) and \( f_{\text{refl}}(\nu) \) is the reflected fraction at that frequency. We compute the line optical depth \( \tau_l(\nu) \) in the same way we did for the reflected fraction, i.e. we assume that all the gas has a Gaussian velocity distribution function with characteristic width equal to the sound speed, and sum over all lines with frequencies sufficiently near \( \nu \).

There is one problematic element in evaluating \( f_\nu \): the expression just given assumes that the total column density through which the continuum passes is the same as the column density visible
by reflection. While this is certainly the minimum, there may be additional matter in regions obscured by the torus. We also know much less about the obscured gas’s physical state. Our only guide is hydrodynamical simulations, such as those reported in Balsara & Krolik (1993, 1994). Unfortunately, these simulations indicate that whether the reflection region can be used to make a good prediction of $\Xi$ and $T$ in the hidden region depends on additional poorly known parameters such as the detailed shape of the inner edge of the torus and its specific angular momentum. To cope with this uncertainty, the results we present (Figures 7) show the effect of only the visible gas; in order to estimate the impact of the hidden gas the best one can do is imagine multiplying the optical depths by factors of several.

In all four models we have examined, three features stand out most clearly in the predicted transmission spectra: K edges of OVII or OVIII; the K edges of the Fe ionization stages within a few of FeXX; and the L edges of those same Fe ionization stages. Their relative strengths vary, of course, depending on the parameters, but in most of the likely range the absorption trough near 1 keV produced by OVII/OVIII and Fe L-absorption (plus assorted lines) is larger than the Fe K absorption. Only in the most highly ionized case (Model c) is the Fe K edge competitive with the 1 keV feature.

Calculations of soft X-ray opacity have traditionally included only photoelectric absorption and sometimes Compton scattering (e.g. Krolik & Kallman 1984; Netzer 1993; Turner et al. 1993). We find that in these circumstances (i.e. relatively strong ionization), while photoelectric absorption is the most important source of opacity, resonance line scattering can also be significant. While our transmitted spectrum for Model b is qualitatively similar to Netzer’s (1993) U=10 case (the closest to ours in ionization level), there are important differences more apparent in the higher ionization models. For example, in Model a the optical depth due to merged resonance lines in the vicinity of 1 keV is typically $\sim 0.3 \times$ the optical depth due to photoelectric absorption, although of course this figure varies by factors of several as a function of wavelength, and depends significantly on the degree of velocity broadening.

The placement of line opacity can also be important. Again referring to Model a, we find that the apparent low energy edge of the absorption trough due to K-shell photoionization of O falls at $\simeq 750$ eV, nearly equal to the OVII edge of 739 eV, even though the abundance of OVIII, whose ionization threshold is 871 eV, is $\sim 100\times$ greater than the abundance of OVII in this model. Thus, merged lines could easily cause a misidentification of the O ionization state.

To be precise, the total spectrum one measures is the sum of the direct flux as filtered by absorption (Figures 5) and the intrinsic emission (Figures 3). This same point is emphasized by Netzer (1993). Our definition of absorption already takes into account scattering. However, unless the optical depth is great enough to absorb a significant fraction of the continuum power, the luminosity of the intrinsic emission is a small fraction of the direct luminosity; for example, in model a even the OVIII L$\alpha$ line has an equivalent width relative to the transmitted continuum of only $\simeq 10$ eV. We expect, therefore, that even the strongest intrinsic lines will only occasionally
In the ultraviolet, the situation is quite different. As remarked above, only a few lines (the HI Lyman series, OVI λ1034, and NV λ1240) have any significant optical depth, and the last two only become interesting if the ionization level is as low as in Model b. The only continuum feature, of course, is the Lyman edge, but its optical depth in these conditions is generally $\sim 0.1 \tau_T \ll 1$. Consequently, we expect this gas to have little impact on the UV spectrum seen in transmission.

The absorption and scattering we predict might, in some circumstances, generate a significant radiation force on the gas (cf. Reynolds & Fabian 1994). In most cases (e.g. Model a), the increase above the radiation force due to Thomson scattering is only a few tens of percent. Although the opacity at 1 keV is several times Thomson, the band in which the opacity is enhanced carries only $\sim 10\%$ of the total flux. However, if the gas is more weakly ionized (as in Model b), the radiation force might be as much as double that due to Thomson scattering alone.

6. Time-Dependent Effects

In our discussion so far we have assumed that the ionizing flux is constant. In view of the substantial variations often observed in the UV and X-ray fluxes of AGN, it is now time to examine that assumption more carefully.

Consider a model equation for the abundance of a particular ionization stage of a photoionized element:

$$\frac{dn_i}{dt} = -[F_i \sigma_{\text{ion},i} + n_e \alpha_{\text{rec},i-1}] n_i + n_e n_{i+1} \alpha_{\text{rec},i} + F_{i-1} \sigma_{\text{ion},i-1} n_{i-1},$$

(15)

where we have neglected Auger ionization, collisional ionization, and three-body recombination. The products $F_i \sigma_{\text{ion},i}$ are meant to be the ionizing (photon number) fluxes for stage $i$ appropriately integrated over the frequency-dependent ionization cross sections $\sigma_{\text{ion},i}$, while $\alpha_{\text{rec},i}$ is the recombination coefficient for producing stage $i$. If the ionizing flux is a function of time, the (formal) solution of this equation is

$$n_i(t) = \exp[- \int_0^t dt' P_i(t')] \int_0^t dt' [n_e n_{i+1} \alpha_{\text{rec},i} + F_{i-1} \sigma_{\text{ion},i-1} n_{i-1}] \exp[\int_0^{t'} dt'' P(t'')],$$

(16)

where

$$P_i(t) = F_i(t) \sigma_{\text{ion},i} + n_e \alpha_{\text{rec},i-1}.$$  

(17)

That is, the abundance of stage $i$ is given by the integrated creation rate of stage $i$ extended over a time $t_d$ which is roughly the typical time for destruction of an ion of stage $i$, whether by ionization or by recombination.

The character of the time-variation of ionic abundances depends on two ratios: $t_d/t_{\text{var}}$, where $t_{\text{var}}$ is the shortest timescale on which order unity fluctuations in the ionizing luminosity occur,
or, if the fluctuations are never that great, the timescale on which most of the variance in the ionizing luminosity is accumulated; and \( \langle (L_{\text{ion}} - \langle L_{\text{ion}} \rangle)^2 \rangle^{1/2} / \langle L_{\text{ion}} \rangle \), the ratio of the rms variation amplitude to the mean value of the ionizing luminosity. When \( t_d \ll t_{\text{var}} \), the ionization state is in equilibrium with the ionizing flux, but there is no steady-state. However, if the amplitude of variability is small, the departures from the mean are small. When \( t_d \gg t_{\text{var}} \), the ionic abundances reach a steady state defined by the mean values of the ionization and recombination rates, but this steady state is almost never in equilibrium with the instantaneous value of the ionizing flux. Again, the differences are small unless the amplitude of variation is substantial. Finally, if \( t_d \sim t_{\text{var}} \), the ionic abundances follow a history which is a smoothed and delayed version of the history of the ionizing flux. In this case, the abundances are neither in a steady state nor in equilibrium. No matter what the value of \( t_d/t_{\text{var}} \) is, the abundance of ion \( i \) cannot change substantially in a time short compared to \( t_d \); in fact, observed variations in the relative abundances may be used to place an upper bound on \( t_d \), and hence an upper bound on the distance between the absorbing matter and the source of ionizing photons.

To decide which case applies, we must estimate \( t_d/t_{\text{var}} \). Before doing so, we point out that \( t_d \) can vary by orders of magnitude from one ion to the next, even for ions of the same element. Typical continuum spectra can often be described by \( F_\nu \propto \nu^{-\alpha} \) with \( 0.5 < \alpha < 2 \). Ionization potentials in mid-Z elements range over roughly two orders of magnitude in energy, so the number fluxes of ionizing photons can have mutual ratios as large as \( \sim 10^{2\alpha} \). Consequently, different ionization stages of the same element can be in quite different regimes with respect to the ratio \( t_d/t_{\text{var}} \).

Earlier, when we argued that, measured on a flow time, the ionization balance stays very close to equilibrium, we estimated \( t_d \) (for the fiducial ion OVIII) by setting it equal to \( t_{\text{recomb}} \equiv [n_e \alpha_{\text{rec}, i} n_{i+1}/n_i]^{-1} \); that is appropriate when \( n_{i-1} \ll n_i \) and the balance is near equilibrium. Using the same approximation, but evaluating \( t_{\text{recomb}} \) for OVIII in time units, we find

\[
 t_{\text{recomb}}(\text{OVIII}) = 12 \frac{n(\text{OVIII})}{n(OIX)} \left( \frac{\tau T_6}{0.01} \right)^{-2} T_6^{-0.3} \left( \frac{\Xi}{10} \right)^{-1} L_{\text{ion,44}} \text{ yr},
\]

where \( L_{\text{ion,44}} \) is the ionizing luminosity normalized to \( 10^{44} \text{ erg s}^{-1} \). Note that the abundance ratio depends strongly on conditions: in our models it ranged from 0.003 in Model c, to \( \simeq 0.03 \) in Models a and d, to \( \simeq 0.9 \) in Model b.

There is no object in which \( t_{\text{var}} \) is well determined. The timescale on which most of the variance is accumulated seems in many cases to be \( \gtrsim 1 \text{ yr} \), and the amplitudes of the fluctuations are generally order unity compared to the very long-term time average fluxes (Edelson, Krolik, & Pike 1990 for the UV; Green, McHardy, & Lehto 1993 for the X-ray). In many cases the power spectrum of fluctuations has a power-law character over a substantial dynamic range in frequency, so there can also be fluctuations of order unity compared to the local mean flux on much shorter timescales. Given this wide range of variability properties, our estimate for \( t_d(\text{OVIII}) \) indicates that \( t_d \) for that ion could be anywhere within one to two orders of magnitude larger or smaller...
than $t_{var}$. Consequently, one must be very careful about which mean flux level is used to compute the current ionization state.

The properties we observe are further averaged over the region. True emission and scattering are integrated over the entire volume, requiring an average over the light crossing time, possibly years to decades or even centuries. If $t_{var}$ is at most a few years, this average may be comparatively stable. However, absorption carries information only about locations on the direct line of sight, so all the sub-regions may be regarded as effectively coherent in time. Thus, absorption properties are directly sensitive to the problems of ionization disequilibrium we have just pointed out. This provides yet an additional reason why “predicted” transmission spectra such as those shown in Figure 7 must be regarded as illustrative at best.

7. Comparison with Observations

7.1. Unobscured AGN

_Ginga_ and _Rosat_ data indicate that the X-rays in a number of unobscured AGN pass through “warm absorbers” on their way to us (e.g. Pounds et al. 1993; Nandra & Pounds 1994). The main observational signatures of this material are Fe K edges with optical depths $\sim 0.1$ at energies corresponding to ionization stages of Fe around FeXX, and edges of OVII and OVIII with optical depths $\sim 0.1 - 1$. ASCA data, with its much greater spectral resolution, should permit a tremendous refinement of this picture (Inoue 1993). Because these identifications have been found by the model-fitting which is customary in X-ray spectroscopy, it is quite possible that many other features may also be present. Absorption of this character is very nicely in line with the predictions we have made here. We therefore suggest that these “warm absorbers” can be identified with the warm, reflecting gas we have been discussing in this paper (cf. Krolik & Kallman 1987, Nandra & Pounds 1994), and its inner, hidden extension.

Interpreting these data requires great care. Both true absorption opacity and scattering must be included if one desires a reasonably accurate description of the frequency-dependent opacity. Blended lines may significantly shift the apparent energy of absorption edges, leading to misidentification of the ion responsible. Unfortunately, as we discussed in §4, consideration of resonance line opacity requires the introduction of at least two more free parameters, one specifying the covering factor, the other the width of the material’s velocity distribution.

In addition (a similar point was made by Netzer 1993 in a somewhat different context), because a large number of lines and edges contribute to the absorption opacity, if one fits models to the data it is preferable to fit well-defined complete photoionization models, rather than individual features. This procedure does not materially increase the number of free parameters (one need
specify only $T$, $\Xi$, and $\tau_T$, as compared to, e.g. the energies and optical depths of several edges), but it should improve the quality of the fits, and possibly reveal features that might otherwise be left as residuals.

However, even this procedure has its limitations. First, contrary to what is frequently done, in this situation there is no need to impose thermal balance on the models (§2) (in fact, the models of Turner et al. 1993 are an example of this practice—their temperature was fixed, somewhat arbitrarily, at $10^5$K). Rather than finding that ionization parameter whose equilibrium temperature is such that the ionization structure best fits the data, one can only restrict the state of the warm absorber to a region in the $\Xi - T$ plane. For example, on the basis of the models shown here, we can already say that in most type 1 Seyfert galaxies, the column density of material as weakly ionized as in Model b must be considerably less than $10^{23}$ cm$^{-2}$; otherwise there would be consistently more soft X-ray absorption observed.

Second, there are likely to be numerous examples in which there is no need to impose strict ionization balance on the models (§6). Whether ionization balance can be expected in any particular case must be evaluated on the basis of the specifics of that case— which ion(s) are important, the mean luminosity of the AGN, and the variability properties of that AGN. The general sense of the effect of departures from ionization balance is that the ionic abundances we observe reflect an average over the recent history of the AGN’s ionizing luminosity, and should therefore change more slowly than the instantaneous luminosity. Additional complications are introduced by the fact that different ions average over different lookback times. However, even this generality cannot be followed blindly, for most AGN light curves are drastically under-sampled. Consequently, it can be very difficult to estimate the correct average fluxes, or even determine whether substantial variation in the ionizing flux has occurred.

The behavior of the “warm absorber” in MCG 6-30-15 observed by Fabian et al. (1994) may be an example of several of the subtleties discussed in the preceding paragraphs. They saw the optical depth of a feature which they identified as the OVII K edge change from $\sim 0.6$ to $\sim 1.2$ in the span of a month, while the X-ray flux dropped by about a factor of 2. Using photoionization models requiring both thermal and ionization equilibrium, they inferred that the column density had increased while the ionization parameter was roughly constant. We suggest several possible reinterpretations of these data. As we pointed out earlier (§5), a merger of line features with an OVIII edge can masquerade as an edge at the energy of OVII. This identification gains some support from the feature in the residuals spectrum at the energy of the Fe L edge. If this suggestion is correct, the observed change in optical depth would be consistent with fixed column density and ionization equilibrium because in the regime where OVIII dominates OVII, the OVIII abundance itself is inversely proportional to the X-ray flux. However, given the ionizing luminosity of this AGN ($\sim 4 \times 10^{43}$ erg s$^{-1}$, from data in Walter & Fink 1993), the expected recombination timescale for OVIII is $\sim 40(\tau_T/0.01)^{-2}$d if, for example, the conditions of Model a obtain. That would mean the ionization states seen in the two measurements were controlled by the ionizing flux averaged over roughly that length of time preceding the two observations. Because the $1 - 10$
keV flux in that object has been seen to vary over a range of a factor of three in as short a time as three days (McHardy 1990), the instantaneous fluxes measured by ASCA need not be very good guides to the appropriate average fluxes.

Finally, we point out that most of the observed narrow absorption lines seen in the UV spectra of a number of AGN (Voit, Shull, & Begelman; Bahcall et al. 1993; Aldcroft et al. 1994) are almost certainly not due to this warm gas. The warm gas we discuss here might produce measurable absorption in Lyα and OVI λ1034 with an expected width and offset to the blue of several hundred km s$^{-1}$. In fact, Lyα absorption blueshifted by $\sim 1000$ km s$^{-1}$ with no other corresponding metal lines is seen in the spectrum of NGC 5548 (Korista et al. 1994). CIV absorption, however, must come from some other material. In all four of our models, the CIV optical depth (before allowance for velocity gradients) was never more than $\sim 10^{-2}$ because in all cases, the overwhelming majority of C atoms were completely stripped. If there were to be any significant abundance of CIV, the mean ionization stage of Fe would be far below the level inferred from the positions of the observed Fe K edges.

On the other hand, OVII and OVIII edges of moderate optical depth can be produced in either of two ways: They can be created by the conditions discussed in this paper, in which the column density is relatively large, and most O is completely stripped; or they may be created by gas more weakly ionized (so that most O is either OVII or OVIII) having rather smaller column density ($10^{21} - 10^{22}$ cm$^{-2}$). Those modelling efforts which have imposed both ionization and thermal balance have tended to home in on the latter solution because it is achieved for $\Xi$ just below the critical value beyond which no cool equilibria exist. In this state, while most C and N atoms are likewise stripped down to the K shell, there are enough Li-like ions of C, N, and O to produce significant opacity in the resonance doublets CIV λ1549, NV λ1240, and OVI λ1034 (Mathur et al. 1994). However, if the gas is to possess any significant opacity in the transitions of still more weakly ionized species (e.g. the MgII λ2798 line; Mathur 1994), the abundance of OVII and OVIII would certainly be negligible.

These two different mechanisms for creating the observed OVII and OVIII edges may be distinguished most easily by searching for Fe absorption edges. To produce either an Fe K or an Fe L edge of optical depth $\sim 0.1$ or greater requires a column density of at least $\sim 10^{23}$ cm$^{-2}$. Thus, Fe K features of the sort seen in Ginga spectra of AGN (Nandra & Pounds 1994) require the large column density, high ionization state solution; a significant Fe L edge would require the same interpretation. On the other hand, the absence of these features would favor the small column density, lower ionization state solution.

It is possible that material in both states exists in individual AGN. As material is photoionized, heated, and driven off the inner surface of the obscuring torus, it must pass through intermediate stages of ionization before reaching the quasi-steady state on which we have focussed here. In these intermediate stages it would be capable of imposing enough UV line opacity to create the observed UV absorption lines; it would also possess significant opacity in the OVII and OVIII K
edges. However, the time-averaged state of the gas would be more highly ionized, so at any one
time most of the gas mass would be in the more highly ionized state. The two states would then
produce comparable amounts of OVII/OVIII K edge opacity, but the more highly ionized gas
would be responsible for all of the ionized Fe K and L edge opacity. When this condition exists,
interpretation of time-variable O photoionization edges becomes even more complicated than
indicated in our discussion of MCG 6-30-15.

7.2. Obscured AGN

As we have already remarked, the primary emission observable in the UV from this gas is the
nuclear reflection. This is due mostly to Thomson scattering, which has been amply discussed in
the literature, but those few UV resonance lines whose optical depths are greater than the electron
scattering optical depth will appear as emission features in the reflection spectrum. Because
the nuclear spectrum generally shows broad emission features at these same lines, the reflection
contribution to the feature will appear as a comparatively narrow component superposed on the
broad emission line profile. Depending on the projection of the velocity of outflow on our line
of sight, this narrow component could be either redshifted or blueshifted by as much as a few
hundred km s\(^{-1}\). Note that broad emission lines which are not resonance transitions (e.g. the
Balmer lines or CIII\(\alpha\) 1909) should not possess narrow components due to reflection.

In the X-ray range from 0.1 – 10 keV, the warm gas should be visible via a mixture of
Thomson reflection, resonance line reflection, and intrinsic emission. The resulting X-ray spectrum
should be very complex.

Only for NGC 1068 are there published data of sufficiently high quality to make a comparison
with these predictions (Marshall et al. 1993; Ueno et al. 1994). In this case there is a large excess
below 2 keV relative to the extrapolated high energy power law, but about half of this flux is due
to extra-nuclear sources (Wilson et al. 1992). Many emission lines are clearly present between
0.5 and 2 keV, but their identifications are somewhat uncertain, and there is no clear way to
distinguish between a nuclear and an extra-nuclear origin for these lines. Nonetheless, the fact
that there is as much unresolved flux in this band as there is indicates that the gas in the reflection
region must be more highly ionized than Model b because otherwise very little in the way of soft
X-rays would emerge.

In some cases of unobscured AGN (e.g. IC 4329A: Madejski et al. 1994) the column density
of the warm absorber appears to be rather small, \(\sim 10^{21} \text{ cm}^{-2}\). These objects viewed from the
side would have much weaker reflection and intrinsic emission, for both scale \(\propto \tau_T\). All that we
would see in X-rays from these galaxies would be whatever portion of the direct nuclear flux can
penetrate the obscuration (see Krolik et al. 1994 or Ghisellini et al. 1994 for explicit calculations
of how large this might be). Those type 2 Seyfert galaxies with little polarization (Kay 1994) may
be objects like these viewed from an obscured direction.

### 7.3. NGC 4151

The case of NGC 4151 is a bit unusual since it combines features of both the obscured and the unobscured AGN. The kilovolt X-ray continuum is heavily absorbed, but appears to not be completely obscured. The optical and UV continuum is directly visible, yet the spectrum is rich in absorption lines. The most popular model for the X-ray absorption has been a large column ($\sim 1 \times 10^{23}$ cm$^{-2}$) of cold gas which only partially covers the source of the X-ray continuum (e.g. Holt et al. 1980). Recently, however, Weaver et al. (1994a, 1994b) have shown that a warm absorber model that includes partial reflection of the nuclear continuum can fit the X-ray spectrum. The soft X-ray flux in these fits is almost entirely due to a reflection component, leaving little room for intrinsic emission. The historical lack of variability in this soft component (Perola et al. 1986; Pounds et al. 1986; Weaver et al. 1994a) suggests reflection from a source distributed over a region light years in diameter.

We identify the agent of reflection with the warm reflecting gas we have discussed here. If this identification is correct, we would expect the soft X-ray spectrum of this source to exhibit the merged line features shown in Figs. 6. The reflected fraction in NGC 4151 ($\approx 2.5\%$; Weaver et al. 1994b) implies $\tau_T = 0.1$ for $\Delta \Omega/4\pi = 0.25$. This leads to a predicted size $\simeq 0.05(\Xi/10)^{-1}T_6^{-1}$ pc, which would be consistent with the lack of variability if $T_6 \Xi$ were as small as $\approx 1 - 2$.

The morphology of the ionized gas imaged with HST implies that our line of sight passes through a substantial column of optically thick material (Evans et al. 1993). In the context of the obscuration/reflection model, this fact suggests that the warm material on our line of sight is likely to be in a lower state of ionization than the bulk of the warm reflecting gas. The Fe K edge energy also indicates an ionization level similar to, or lower than, our Model b. For this model, the timescale for changes in soft X-ray opacity is $\approx 12(\tau_T/0.1)^{-2}$ d, where we have used an ionizing luminosity of $2.1 \times 10^{43}$ erg s$^{-1}$ (Evans et al. 1993) and the optical depth derived above. (Note that this timescale is significantly longer than the 100 s used by Weaver et al. 1994a, who make the tacit assumption that the absorbing gas is similar to broad-line clouds in density and therefore located much closer to the source for similar ionization parameters.) Our 12 day timescale is consistent with both the BBXRT (Weaver et al. 1994a) and the ASCA (Weaver et al. 1994b) observations. The BBXRT data show a possible, slight increase in absorption below 2 keV in just 0.7d, while the $2 - 10$ keV flux decreases by about 40%. Given the smoothing effects of the 12 d recombination timescale, one expects only small changes in opacity over a day in response to even large continuum fluctuations. The ASCA data (Weaver et al. 1994b), comprising two observations separated by about five months, show large changes in soft X-ray opacity, even while the intrinsic $2 - 10$ keV flux increases by only about 20%. This behavior is again consistent with our previous
arguments that the ionization structure need not reflect the instantaneous continuum, but rather an average over the variations occurring over roughly the preceding recombination timescale. This would require monitoring for $\sim 12$ days to adequately constrain a physical model for the absorber.

8. Conclusions

We have shown that X-ray heated winds in AGN may manifest their presence in many ways. In addition to serving as the warm reflecting gas that permits us to view the inner regions of obscured AGN, the wind may produce the “warm” absorption seen in many AGN X-ray spectra. Our models provide a qualitative match to many of the observed properties of both obscured and unobscured AGN.

The X-ray emission from the wind is dominated by line radiation superposed on bremsstrahlung plus recombination continua. This may be visible in obscured AGN if the nucleus can be isolated from the surrounding galaxy, but the nuclear continuum reflected by Thomson scattering and by resonance line scattering will be comparable or greater in brightness. The strong kilovolt emission lines visible in the X-ray spectra of obscured AGN may be produced by both intrinsic emission and resonance scattering in the X-ray heated wind. The UV emission is principally bremsstrahlung plus recombination lines of H and He. Reflection of the nuclear continuum by Thomson scattering will dominate the UV spectrum, but there will be some contribution from resonance lines. These lines would be difficult to distinguish from emission in the narrow-line region, but they might be most easily visible as narrow features in a polarized flux spectrum.

In unobscured AGN the reflected and intrinsic components of the gas are swamped by the nuclear continuum, but absorption by the resonance lines and photoionization edges of highly ionized species will imprint their signature on the transmitted spectrum. The presence of merged line features can seriously complicate the identification of edges. The high columns required to produce Fe K edges in *Ginga* X-ray spectra and comparable OVII and O VIII edges in *ROSAT* spectra correspond nicely to our predictions.

Absorption in the UV, however, is expected to be weak. Only the Lyman lines reach significant optical depth, and there is some contribution from the OVI and NV resonance doublets in the lowest ionization models. Most UV lines observed in AGN must come from lower ionization gas with a lower column density than that producing the Fe K edges; this gas could be an intermediate state in the production of the more highly ionized reflecting gas.

Time scales for variations in the emitted and reflected components of the wind should be years or longer since the gas fills a region parsecs or more in size in a typical AGN. Sight lines for absorption, however, are effectively coherent in time, and the time-dependent effects are a function of the variability timescales in the active nucleus as well as the timescales for ionization equilibration. For typical AGN the transmission spectrum may not be well described by models in
ionization equilibrium, and the response to continuum variations is smoothed over recombination
timescales that could be, depending on circumstances, anywhere from days to years.

We thank Ski Antonucci, Chris Done, and Andy Fabian for stimulating conversations and
acquainting us with unpublished data.

This work was partially supported by NASA Grants NAGW-3516 and NAG5-1630 and NASA
contract NAS-5-27000 to the Johns Hopkins University.
| Line      | Model a | Model b | Model c | Model d |
|----------|---------|---------|---------|---------|
| Lyα      | 2.60    | 55.8    | 0.263   | 5.32    |
| CIV λ1549| 2.78 × 10^{-4} | 0.0199 | 2.95 × 10^{-7} | 1.36 × 10^{-5} |
| NV λ1240 | 4.42 × 10^{-4} | 0.215  | 4.60 × 10^{-7} | 1.19 × 10^{-4} |
| OVI λ1034| 0.0209  | 34.2    | 2.10 × 10^{-5} | 0.0150  |

Table 1: Optical Depths of UV Absorption Lines

Note: These optical depths are based on a total column density of 10^{23} cm^{-2} and thermal velocity widths.
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Fig. 1.— log($\nu F_\nu$) vs. log($\nu$) for our generic spectrum (solid line) and the MF spectrum (dotted line).

Fig. 2.— The radiative equilibrium curve of $T$ vs. $\Xi$ for our generic spectrum (solid line) and the MF spectrum (dotted line). The letters mark the four points at which we have computed warm reflection region models.

Fig. 3.— Soft X-ray spectra emitted by the warm plasma, in units of $L_{44}N_{23}(\Delta \Omega/\pi)$ erg s$^{-1}$ eV$^{-1}$. The solid curve shows the total of emission lines and continua, smoothed by a Gaussian of constant fractional width $\Delta \nu/\nu = 0.05$. The dotted curve shows the portion due to bremsstrahlung and recombination continua alone, with no smoothing. Note that the vertical scale is compressed by a factor of four relative to the horizontal scale. The temperature and ionization parameter are given in the lower left corner of each panel, and the letters correspond to the four models identified in Fig. 2.

Fig. 4.— The intrinsic emission spectrum in the ultraviolet in units of $L_{44}N_{23}(\Delta \Omega/\pi)$ erg s$^{-1}$ Å$^{-1}$.

Fig. 5.— Reflected fraction as a function of frequency.

Fig. 6.— Reflected plus intrinsic soft X-ray spectrum in units of $L_{44}N_{23}(\Delta \Omega/\pi)$ erg s$^{-1}$ eV$^{-1}$.

Fig. 7.— Transmission fraction in the soft X-ray band as a function of frequency, including those photons scattered into the observer’s line of sight from other directions. The covering fraction of the absorbing material is taken to be 1/4. The transmission fraction for pure electron scattering is shown as a dashed line. Note that the zero has been suppressed on the vertical scale to show the spectral features more clearly.