ON THE REDDENING IN X-RAY–ABSORBED SEYFERT 1 GALAXIES

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ABSTRACT

There are several Seyfert galaxies for which there is a discrepancy between the small column of neutral hydrogen deduced from X-ray observations and the much greater column derived from the reddening of the optical/UV emission lines and continuum. The standard paradigm has the dust within the highly ionized gas that produces O VII and O VIII absorption edges (i.e., a “dusty warm absorber”). We present an alternative model in which the dust exists in a component of gas in which hydrogen has been stripped, but which is at too low an ionization state to possess significant columns of O VII and O VIII (i.e., a “lukewarm absorber”). The lukewarm absorber is at sufficient radial distance to encompass much of the narrow emission line region and thus accounts for the narrow-line reddening, unlike the dusty warm absorber. We test the model by using a combination of photoionization models and absorption edge fits to analyze the combined ROSAT/ASCA dataset for the Seyfert 1.5 galaxy, NGC 3227. We show that the data are well fitted by a combination of the lukewarm absorber and a more highly ionized component similar to that suggested in earlier studies. We predict that the lukewarm absorber will produce strong UV absorption lines of N V, C IV, Si IV, and Mg II. Finally, these results illustrate that singly ionized helium is an important, and often overlooked, source of opacity in the soft X-ray band (100–500 eV).

Subject headings: galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

The presence of absorption edges of O VII and O VIII in the X-ray (Reynolds 1997; George et al. 1998) indicates that there is a significant amount of intrinsic ionized material along our line of sight to the nucleus in a large fraction (~0.5) of Seyfert 1 galaxies. In addition to highly ionized gas (referred to as an X-ray or “warm” absorber), X-ray spectra often show evidence for a less-ionized absorber. This component has been modeled using neutral gas (cf. George et al. 1998), and its relationship to the “warm” absorber is unclear. Interestingly, there are several instances in which this additional neutral column is too small by as much as an order of magnitude to explain the reddening of the continuum and emission lines, assuming typical Galactic dust/gas ratios (cf. Shull & Van Steenberg 1985). This inconsistency was first noted in regard to the absence of high ionization emission lines in the IUE spectra of MCG –6-30-15 (Reynolds & Fabian 1995). The first quantitative comparison of the neutral columns inferred from the X-ray data to that derived from the reddening was for the QSO IRAS 13349+2438 by Brandt, Fabian, & Pounds (1996), who suggested that the dust exists within the highly ionized X-ray absorber (ergo, a dusty warm absorber). It has been suggested that dusty warm absorbers are present in several other Seyfert galaxies (NGC 3227: Komossa & Fink 1997a; NGC 3786: Komossa & Fink 1997b; IRAS 17020+4544: Leighly et al. 1997, Komossa & Bade 1998; MCG –6-30-15: Reynolds et al. 1997). Since it is unlikely that dust could form within the highly ionized gas responsible for the O VII and O VIII absorption, it has been suggested that the dust is evaporated off the putative molecular torus (at ~1 pc) and, subsequently, swept up in an radially outflowing wind (cf. Reynolds 1997).

In this paper, we present an alternative explanation. It is possible that there is a component of dusty gas (which we will refer to as the “lukewarm” absorber), with an ionization state such that hydrogen is nearly completely ionized but the O VII and O VIII columns are negligible, which has a sufficient total column to account for the reddening. This possibility has been mentioned by Brandt et al. (1996), while Reynolds et al. (1997) have suggested that the dusty warm absorber in MCG–6-30-15 may have multiple zones. Such a component has been detected in the Seyfert galaxy NGC 4151 (Kraemer et al. 1999), and it lies at sufficient radial distance to cover much of the narrow-line region (NLR). We will demonstrate that the combination of a dusty lukewarm absorber and a more highly ionized (O VII and O VIII) absorber is consistent with the observed X-ray data and with the reddening of the narrow emission lines in the Seyfert 1 galaxy NGC 3227.

2. ABSORPTION AND REDDENING IN NGC 3227

NGC 3227 (z = 0.003) is a well-studied Sb galaxy with an active nucleus, usually classified as a Seyfert 1.5 (Osterbrock & Martel 1993). X-ray observations of NGC 3227 with ROSAT and ASCA reveal the presence of ionized gas along the line of sight to the nucleus (Ptak et al. 1994; Reynolds 1997; George et al. 1998). Using the combined ASCA and ROSAT data set obtained in 1993, George et al. (1998) characterized the absorber with an ionization parameter (number of photons with energies ≥ 1 ryd per hydrogen atom at the ionized face of the cloud) U ≈ 2.4 and a column density N_H ≈ 3 × 10^{21} cm^{-2}.

The UV and optical emission lines and continuum in NGC 3227 are heavily reddened. Cohen (1983) measured a
narrow Hα/Hβ ∼ 4.68 and derived a reddening of $E_{B-V} = 0.51 \pm 0.04$, assuming the intrinsic decrement to be equal to the Case B value (Osterbrock 1989). Cohen derived a somewhat larger reddening from the [S II] lines, $E_{B-V} = 0.94 \pm 0.23$, which may be less reliable owing to the weakness of [S II] λ6717 (cf. Wampler 1968). The ratio of broad Hα/Hβ ∼ 5.1, indicating that the broad and narrow lines are similarly reddened. Winge et al. (1995) used the total (narrow + broad) Hα/Hβ ratio to derive a somewhat smaller reddening, $E_{B-V} \approx 0.28$. IUE spectra show the UV continuum of NGC 3227 is also heavily reddened (Kommossa & Fink 1997a). Based on the Balmer lines, assuming Galactic dust properties and dust/gas ratio, the derived reddening requires a hydrogen (H I and H II combined) column density $\geq 2 \times 10^{21}$ cm$^{-2}$ (cf. Shull & Van Steenberg 1985), which is much greater than the estimated neutral column, but similar to that of the ionized gas detected in X-rays in 1993 ($N_H \approx 3 \times 10^{21}$ cm$^{-2}$; George et al. 1998b).

Several workers have suggested that NGC 3227 contains a screen of neutral material (in addition to that in the Galaxy) along the line of sight to the nucleus. Besides the ionized absorber, both Kommossa & Fink (1997a) and George et al. (1998b) found a column density of $\leq 3 \times 10^{20}$ cm$^{-2}$ of neutral material, in addition to the Galactic column ($\sim 2.1 \times 10^{20}$ cm$^{-2}$; cf. Murphy et al. 1996). It is required to model the X-ray spectrum below $\sim 500 \text{ eV}$. A higher column density ($\sim 6 \times 10^{20}$ cm$^{-2}$) has been suggested based on 21 cm VLA observations (Mundell et al. 1997). However, the angular resolution of the VLA data is poor (12" or $\sim 850 \text{ pc}$) and Mundell et al. (1997) did not make a direct detection of H I absorption against the radio continuum source in the inner nucleus. In this paper we argue that based on the current data, there is no reason to include a significant column of completely neutral material. We show that a dusty lukewarm absorber lying outside the NLR is consistent with both the reddening of the optical continuum and narrow lines, and with the attenuation of the X-ray spectrum below $\sim 500 \text{ eV}$.

3. Modeling the Absorber

3.1. Lukewarm Component

The photoionization code we use has been described in previous publications (cf. Kraemer et al. 1994). For the sake of simplicity, we assume that the lukewarm absorber can be represented as a single zone, described by one set of initial conditions (i.e., density, ionization parameter, elemental abundances, and dust fraction). The gas is ionized by the continuum radiation emitted by the central source in the active nucleus of NGC 3227.

In order to fit the SED, we first determined the intrinsic luminosity at the Lyman limit. Since NGC 3227 is heavily reddened, we fitted the value at the Lyman limit based on the optical continuum flux. From the average fluxes measured by Winge et al. (1995), after correcting for a reddening of $E_{B-V} = 0.4$ (the average of the reddening quoted by Cohen 1983 and Winge et al. 1995), assuming the reddening curve of Savage & Mathis (1979), we find that the intrinsic flux at 5525 Å is $F_\lambda \approx 2.5 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. Interestingly, the optical luminosities of NGC 3227 and NGC 4151 are roughly equal, and, therefore, we have made the assumption that the two galaxies have similar optical–UV SEDs. Using the same ratio of optical to UV flux for NGC 3227 as in NGC 4151 (Nelson et al. 1999), we determine $F_\nu$ at the Lyman limit to be $\sim 6.2 \times 10^{-26}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$. The X-ray continuum from 2 to 10 keV can be fitted with an index, $\alpha \approx 0.6$ (George et al. 1998b), from which we derive a flux at 2 keV of $\sim 2.20 \times 10^{-29}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$. Since an extrapolation of the X-ray continuum underpredicts the flux at the Lyman limit by more than 2 orders of magnitude, the continuum must steepen below $2 \text{ keV}$. Hence, we have modeled the EUV to X-ray SED as a series of power-laws of the form $F_\nu \propto \nu^{-\alpha}$, with $\alpha = 1$ below 13.6 eV, $\alpha = 2$ over the range 13.6 eV $\leq h\nu < 500 \text{ eV}$, and $\alpha = 0.6$ above 500 eV.

Given this simple parameterization, the steepening of the continuum cannot occur at a much lower energy; otherwise, the EUV continuum would be too soft to produce the observed He II λ4686/Hβ ratio ($\sim 0.23$), specifically since the strong [O I] λ6300 line indicates that much of the NLR gas is optically thick (for the relative narrow emission-line strengths, see Cohen 1983). The luminosity in ionizing photons, from 13.6 to 10,000 eV, is $\sim 1.5 \times 10^{53}$ photons s$^{-1}$.

We have assumed roughly solar element abundances (cf. Grevesse & Anders 1989), which are, by number relative to H, as follows: He = 0.1, C = 3.4 $\times 10^{-4}$, N = 1.2 $\times 10^{-4}$, O = 6.8 $\times 10^{-4}$, Ne = 1.1 $\times 10^{-4}$, Mg = 3.3 $\times 10^{-5}$, Si = 3.1 $\times 10^{-5}$, S = 1.5 $\times 10^{-5}$, and Fe = 4.0 $\times 10^{-5}$. We assume that both silicate and carbon dust grains are present in the gas, with a power-law distribution in sizes (see Mathis, Rumpl, & Nordsieck 1977). Thus, we have modified the abundances listed above by depletion of elements from gas-phase onto dust grains, as follows (cf. Snow & Witt 1996): C, 65%; O, 50%; Si, 94%; Mg, 82%; and Fe, 95%.

For our model, we require that (1) the absorber lies outside the majority of the NLR emission, and (2) the column of gas is fixed to obtain the observed reddening. Based on the WFPC2 narrowband [O iii] λ5007 imaging (Schmitt & Kinney 1996), we have placed the lukewarm absorber at least 100 pc from the central source and have truncated the model at a hydrogen column density $N_H = 2 \times 10^{21}$ cm$^{-2}$. We adjusted the ionization parameter such that the model produced a reasonable match to the absorption in the observed soft X-ray continuum (see below).

3.2. Comparison to the X-Ray Data

To compare our model predictions to the X-ray data, we used the 1993 ASCA (0.6–10 keV) and ROSAT PSPC (0.1–2.5 keV) data described in George et al. (1998b), excluding the flare ("t3" in Fig. 4 of George et al. 1998b). Following standard practice, the normalizations of each of the four ASCA instruments and of the ROSAT data set were allowed to vary independently. The 5–7 keV band was also excluded from the analysis owing to the presence of the strong, broad Fe emission line. We assumed the continuum described above, except that the spectral index above 500 eV was allowed to vary during the analysis. In addition to the lukewarm absorber (and Galactic absorption), any highly ionized gas was modeled by a series of edges of fixed energy. This is somewhat problematic since neither the

\textsuperscript{4} It is possible to have a lower break energy and a sufficient number of He II ionizing photons if the EUV continuum has a significant "Big Blue Bump," as suggested by Mathews & Ferland (1987). Although assuming such a continuum does not appreciably affect our predictions, a full exploration of parameter space is beyond the scope of this paper.
ASCA nor ROSAT instruments have sufficient spectral resolution and/or sensitivity to resolve all the possible edges. We have therefore tested for the edges most likely to be visible in highly ionized gas (e.g., O \text{ VII} and O \text{ VIII}).

An acceptable fit to the data was obtained ($\chi^2 = 1195$ for 1176 degrees of freedom; $\chi^2 = 1.02$) with the following parameters for the lukewarm absorber: $U = 0.13$, $n_H = 20$ cm$^{-3}$, and the distance of the cloud from the ionizing source is $\approx 120$ pc. The predicted electron temperature at the ionized face of this component is $\approx 18,000$ K, and, therefore, it is thermally stable (cf. Krolik, McKee, & Tarter 1981). The best fitting value for the spectral index above 500 eV was 0.58 $\pm$ 0.03, consistent with our initial assumptions. We find evidence of absorption by several ions, with the following column densities: C\text{ V}, $6.5 \times 10^{17}$ cm$^{-2}$; O\text{ VI}, $2.9 \times 10^{17}$ cm$^{-2}$; O\text{ VII}, $7.8 \times 10^{17}$ cm$^{-2}$; O\text{ VIII}, $1.0 \times 10^{18}$ cm$^{-2}$; and Ne\text{ IX}, $4.9 \times 10^{17}$ cm$^{-2}$. The O\text{ VII} and O\text{ VIII} edges translate to an effective hydrogen column density of highly ionized gas of $\gapprox 2 \times 10^{21}$ cm$^{-2}$. The data/model ratios from this fit are shown in Figure 1. The slight

![Graph showing spectral components and data/model ratios](https://example.com/graph)

Fig. 1—Upper panel: The spectral components described in the text. The SED in the EUV (dotted line) is represented by the three power laws described in § 3.1. This is attenuated by a highly ionized absorber (giving rise to the O\text{ VII} and O\text{ VIII} edges), and a dusty lukewarm absorber (giving rise to the H\text{ I} and He\text{ II} edges, as well as additional opacity throughout the spectrum below $\approx 1$ keV). Finally, the spectrum is attenuated by Galactic absorption leading to the observed spectrum (bold line). Lower panel: The data/model ratios for the ROSAT PSPC data (open circles) and ASCA SIS data (filled triangles). The SIS data are weighted means of the two instruments. Both the PSPC and SIS data sets have been rebinned in energy space for clarity. The 5–7 keV band was excluded from the analysis owing to the intense Fe K-shell emission (open triangles).

**TABLE 1**

**LUKEWARM MODEL: IONIC COLUMN DENSITIES** (cm$^{-2}$)

| Element | I   | II   | III  | IV   | V   | VI   | VII  | VIII | IX  | X   |
|---------|-----|------|------|------|-----|------|------|------|-----|-----|
| H       | $1.6 \times 10^{18}$ | $2.1 \times 10^{21}$ | $7.3 \times 10^{19}$ | 1.3 $\times 10^{20}$ | ... | ... | ... | ... | ... | ... |
| He      | $4.3 \times 10^{16}$ | ... | $5.2 \times 10^{16}$ | $7.6 \times 10^{16}$ | ... | ... | ... | ... | ... | ... |
| C       | ... | $1.4 \times 10^{18}$ | $5.3 \times 10^{16}$ | ... | ... | ... | ... | ... | ... | ... |
| N       | ... | $7.6 \times 10^{14}$ | $9.6 \times 10^{16}$ | ... | ... | ... | ... | ... | ... | ... |
| O       | ... | $2.7 \times 10^{18}$ | $2.6 \times 10^{17}$ | ... | ... | ... | ... | ... | ... | ... |
| Ne      | ... | $3.4 \times 10^{14}$ | $7.3 \times 10^{16}$ | ... | ... | ... | ... | ... | ... | ... |
| Si      | ... | $6.5 \times 10^{13}$ | $1.6 \times 10^{14}$ | ... | ... | ... | ... | ... | ... | ... |
| Mg      | ... | $6.3 \times 10^{15}$ | $2.6 \times 10^{15}$ | ... | ... | ... | ... | ... | ... | ... |

*Columns less than $10^{13}$ cm$^{-2}$ are not listed.*
overprediction of the absorption below 300 eV in the 
ROSAT band is easily rectified by a small (~20%) decrease in 
the column density of the lukewarm absorber.

The ionic column densities for the lukewarm absorber are 
listed in Table 1, and, as expected, the column densities of 
O vii and are too small to make detectable contributions to 
the X-ray absorption edges ($\tau_{\text{O vii}} < 0.01$, as opposed to 
~0.19 for the highly ionized gas). Therefore, this component 
does not resemble the X-ray absorbers most frequently 
discussed to date (e.g., Reynolds 1997; George et al 1998a). 
On the other hand, the model predicts substantial columns for H I, N v, Si iv, C iv, and Mg ii, which would 
result in strong and, for the most part, saturated UV resonance 
absorption lines.

\textit{ASCA} observed NGC 3227 again in 1995. George et al 
(1998b) have shown that during this epoch the observed 
spectrum was significantly different, consistent with a thick, 
highly ionized cloud moving into and attenuating ~85% of 
the line of sight to X-ray source. According to our hypothe-
sis, the lukewarm absorber is located >100 pc from the 
nucleus; hence, we do not expect it to have varied between 
these two epochs. We have therefore checked and found 
that indeed the 1995 \textit{ASCA} data are consistent with the soft 
X-ray attenuation from our lukewarm absorber. (However, 
the lack of simultaneous \textit{ROSAT} PSPC data during 1995 
prevents a stringent test.)

4. DISCUSSION

We have shown that the X-ray spectrum of NGC 3227 is 
consistent with attenuation by the sum of a highly ionized 
absorber and a lukewarm absorber. We suggest that these 
are physically different components of the circumnuclear 
material surrounding NGC 3227. The characteristics of the 
highly ionized absorber are similar to those previously sug-
gested for NGC 3227 (George et al. 1998b); this is in the 
range of and generally similar to those in other Seyfert 1 
galaxies (Reynolds 1997; George et al. 1998a). Such 
absorbers have been observed to vary on timescales <3 yr 
(and much faster in some cases), and are probably the result of 
gas well within the NLR.

The main result of this paper is that the second com-
ponent, our “lukewarm absorber,” has the appropriate 
physical conditions to explain simultaneously the absorption 
seen below 0.5 keV in the X-ray band (previously modeled as completely neutral gas) and the reddening seen in 
the optical/UV. Agreement with the soft X-ray data is the 
result of the lukewarm gas containing significant opacity due to He ii. Agreement with the reddening of the narrow 
emission lines places the component outside the NLR.

Although the lukewarm absorber has the appropriate 
physical conditions and radial distance to reden the NLR, 
it must also have a sufficiently high covering fraction to be 
detected. For example, Reynolds (1997) found that four of 
20 of radio-quiet active galaxies show both intrinsic X-ray 
absorption and reddening. Thus, the global covering factor 
of the dusty ionized absorber must be 20%, within the solid 
angle that we see these objects (cf. Antonucci 1993).

Kraemer et al. (1999) have shown that the covering factor 
for optically thin gas in NGC 4151, similar to our lukewarm 
model, can be quite large (~30%). In addition, Crenshaw 
et al. (1999) find that ~60% of Seyfert 1 galaxies have UV 
absorbers with a global covering factor ≥50%, and an ion-
ization parameter similar to the lukewarm absorber, but 
with lower columns on average (cf. Crenshaw & Kraemer 
1999). Therefore, it is entirely plausible that there would be 
optically thin NLR gas along our line-of-sight to the 
nucleus in a fraction of Seyfert 1s.

The lukewarm model predicts a column of Mg ii of 
6.3 × 10^{13} cm^{-2}, which would produce strong Mg ii 2800 
absorption. It is interesting that NGC 3227 is one of the few 
Seyfert 1s to show evidence of Mg ii 28000 in absorption 
(Ulrich 1988). While Kriss (1998) has shown that Mg ii 
absorption can arise in clouds characterized by small 
column density and low ionization parameter (N_{H}~10^{19.5} 
cm^{-2}, U~10^{-2-3}), our results predict that it may also arise 
in a large column of highly ionized NLR gas, even if a 
substantial fraction of Mg is depleted onto dust grains.

The lukewarm model predicts average grain tempera-
tures of 30–60 K, for grains with radii from 0.25 to 
0.005 μm, respectively. The reradiated IR continuum, which 
is produced primarily by the silicate grains (cf. Mezger, 
Mathis, & Panagia 1982), peaks near 60 μm. Assuming 
a covering factor of unity, this component only accounts for 
~1% of the observed IR flux from NGC 3227 (which is 
~7.98 Jy at 60 μm; IRAS Point Source Catalog 1985). It is 
likely that most of the thermal IR emission in NGC 3227 
arises in the dense ($n_{H}~10^{3} \text{ cm}^{-3}$) NLR gas in which 
the narrow emission lines are formed, as is the case for the 
Seyfert 2 galaxy, Mrk 3 (Kraemer & Harrington 1986).

5. SUMMARY

Using the combined 1993 \textit{ROSAT/ASCA} data set for 
NGC 3227 and photoionization model predictions, we have 
demonstrated that the observed reddening may occur in 
dusty, photoionized gas that is in a much lower ionization 
state than X-ray absorbers detected (by their O vii and 
O viii edges) in Seyfert 1 galaxies (cf. Reynolds 1997; 
George et al. 1998a) and the dusty warm absorbers that 
have been proposed (cf. Komossa & Fink 1997a). This com-
ponent (the lukewarm absorber) is ~120 pc from the 
central ionizing source, and its physical conditions are 
similar to those in optically thin gas present in the NLR of 
the Seyfert 1 galaxy NGC 4151. If this model is correct, we 
predict that strong UV resonance absorption lines with 
high column densities from the lukewarm absorber will be 
oberved in NGC 3227.

We have confirmed earlier results regarding the presence 
of an X-ray absorber within NGC 3227 with O vii and 
O viii optical depths similar to those determined by Rey-
nolds (1997). This component lies closer to the central 
source than the lukewarm absorber but is essentially trans-
parent to EUV and soft X-ray radiation and, hence, does 
not effectively screen the lukewarm gas. We find no require-
ment for neutral gas in addition to the Galactic column.

These results illustrate that a moderately large (~10^{21} 
cm^{-2}) column of ionized gas can produce significant soft 
X-ray absorption if much of the helium is in the singly 
ionized state. Since clouds with large He ii columns may be 
a common feature of the NLR of Seyfert galaxies, such a 
component should be included in modeling the X-ray 
absorption. If such a component is present along our line of 
sight in an active galaxy, it is likely that the intrinsic neutral 
column has been overestimated.

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