A STUDY OF THE X-RAYED OUTFLOW OF APM 08279+5255 THROUGH PHOTOIONIZATION CODES

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ABSTRACT

We present new results from our study of the X-rayed outflow of the $z = 3.91$ gravitationally lensed broad absorption line quasar APM 08279+5255. These results are based on spectral fits to all the long exposure observations of APM 08279+5255 using a new quasar-outflow model. This model is based on cloudy\textsuperscript{3} simulations of a near-relativistic quasar outflow. The main conclusions from our multi-epoch spectral re-analysis of Chandra, XMM-Newton, and Suzaku observations of APM 08279+5255 are the following. (1) In every observation, we confirm the presence of two strong features, one at rest-frame energies between 1–4 keV and the other between 7–18 keV. (2) We confirm that the low-energy absorption (1–4 keV rest frame) arises from a low-ionization absorber with $\log(N_H/cm^{-2}) \sim 23$ and the high-energy absorption (7–18 keV rest frame) arises from highly ionized ($3 \lesssim \xi \lesssim 4$, where $\xi$ is the ionization parameter) iron in a near-relativistic outflowing wind. Assuming this interpretation, we find that the velocities on the outflow could get up to $\sim 0.7c$. (3) We confirm a correlation between the maximum outflow velocity and the photon index and find possible trends between the maximum outflow velocity and the X-ray luminosity, and between the total column density and the photon index. We performed calculations of the force multipliers of material illuminated by absorbed power laws and a Mathews–Ferland spectral energy distribution (SED). We found that variations of the X-ray and UV parts of the SEDs and the presence of a moderate absorbing shield will produce important changes in the strength of the radiative driving force. These results support the observed trend found between the outflow velocity and X-ray photon index in APM 08279+5255. If this result is confirmed it will imply that radiation pressure is an important mechanism in producing quasar outflows.

Key words: galaxies: active – quasars: absorption lines – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

The existence of an $M_{\text{BH}}-\sigma$ relation in nearby galaxies (e.g., Ferrarese & Merritt 2000) suggests that a feedback mechanism exists regulating the co-evolution between the massive black hole at the center of a galaxy and the formation of its bulge. Quasar outflows could transport a fraction of the central black hole binding energy to the host galaxy by possibly shocking Quasar outflows could transport a fraction of the central black hole binding energy to the host galaxy by possibly shocking interstellar matter under a broad range of conditions. We have used version (e.g., Ivezic et al. 2002; Jiang et al. 2007).

\textsuperscript{3} cloudy is a photoionization code designed to simulate conditions in interstellar matter under a broad range of conditions. We have used version 08.00 of the code last described by Ferland et al. (1998). The atomic database used by cloudy is described in Ferguson et al. (2001) and http://www.pa.uky.edu/~verner/atomin.html.

\textsuperscript{4} RL AGNs represent between 10\% and 20\% of the whole AGN population (e.g., Ivezic et al. 2002; Jiang et al. 2007).

in high signal-to-noise ratio (S/N) spectra of nearby AGNs (Fukumura et al. 2010). Specifically, Fukumura et al. (2010) find that an MHD model can explain the distribution of absorption as a function of ionization parameter ($d\log N_H/d\xi$) in the X-ray spectra of five nearby AGNs (mostly Seyfert 1 galaxies at $z \lesssim 0.1$). It is not clear if this result can be extended to high-redshift sources or sources with relativistic winds where we expect strong and likely discontinuous gradients of the outflow velocity and therefore we do not expect to find smooth $d\log N_H/d\xi$ distributions as required in their model.

At moderate to high Eddington ratios ($L/L_{\text{Edd}} \gtrsim 0.2$), which may be common in high-redshift sources $z \gtrsim 2$ (Kollmeier et al. 2006), we expect that radiative driving becomes more important than magnetic driving (Everett 2005). Recent observations of the high-redshift ($z \approx 2$) ultraluminous infrared galaxy SMM J1237+6203 suggest a large-scale powerful wind in this object driven by AGN radiation (Alexander et al. 2010). These observations suggest that in high-redshift AGNs ($z \gtrsim 2$) radiatively driven winds may be more common than the jets found in radio galaxies. Radiative driving is also the favorite mechanism for explaining the formation of outflows observed in the UV from broad absorption line (BAL) quasars. Evidence of the latter is found in the correlation between changes in the maximum velocity of the outflow ($C_{\text{IV}}$ absorption lines) as a function of variations in the soft-to-hard spectral slope $\alpha_{\text{ox}}$ (e.g., Gibson et al. 2009). The outflows observed in the UV from BAL quasars usually have moderate velocities ($\lesssim 0.1c$), however, there have been reported cases with velocities of $\sim 0.2c$ (Rodriguez-Hidalgo et al. 2007). Observations (Hamann et al. 2008) of the quasar J105400.40+034801.2 imply wind velocities of $\sim 0.8c$ based on measurements of the C IV line. We
note, however, that even though this source reveals blueshifted broadnings \( \geq 4000 \text{ km s}^{-1} \) in C IV lines, it is not considered a BAL quasar in the strict sense of the definition (i.e., Weymann et al. 1991).\(^5\) Several of the reported low S/N cases of high velocity AGN outflows have led to spurious detections (see Vaughan & Uttley 2008, and references therein). A handful of moderate S/N X-ray spectra of BAL and mini-BAL quasars have been obtained that show strong signatures of fast winds (e.g., Chartas et al. 2002, 2007a, 2007b, 2009b). The velocities of the outflowing X-ray absorbing material in some cases are found to be (\( \geq 0.7c \)) indicating a different dynamical state than the observed outflow in the UV band. The fast variability and high-ionization state of the winds observed in the X-rays could also be indicating that these X-ray outflows are originating closer to the central source than the outflows observed in the UV.

Recently (Saez et al. 2009; Chartas et al. 2009b), we presented observational evidence for the presence of a powerful outflow in BAL quasar APM 08279+5255 based on the analysis of the X-ray spectra of this object. APM 08279+5255 is a high-redshift quasar which is unusually bright due to gravitational lensing, providing the exceptional opportunity to study it with high-quality spectral data. Our conclusions from these studies were that the outflow was accelerated to relativistic speeds and was releasing kinetic energy at a rate comparable to the bolometric luminosity of this source. The latter indicated that this outflow can release an important fraction of the energy produced by black hole accretion into the surrounding galaxy. In our study of APM 08279+5255, we also found evidence that the outflow could be radiatively accelerated by the central source. This paper is laid out as follows. In Section 2, we present the main conclusions extracted from recent studies that focused on long X-ray observations (\( \sim 100 \) ks) of APM 08279+5255 performed with Chandra, XMM-Newton, and Suzaku. We also expand on the previous studies in two directions. First in Section 3 we describe how the use of photoionization models may help us better constrain the physical properties of the outflowing X-ray absorbing gas. Second in Section 4 we discuss how the spectral energy distribution (SED) of the central source may influence the dynamics of the outflow.

Unless stated otherwise, throughout this paper we use CGS units, the errors listed are at the 1\( \sigma \) level, and we adopt a flat \( \Lambda \)-dominated universe with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega _\Lambda = 0.7 \), and \( \Omega _M = 0.3 \).

2. THE FAST OUTFLOW OF APM 08279+5255

This section contains information extracted from past studies of APM 08279+5255. In Section 2.1, we concentrate on general information that is relevant to understanding the origin of the fast outflow of X-ray absorbing material observed in this object. In Section 2.2, we describe the most important results extracted from eight deep X-ray observations of APM 08279+5255.

2.1. Properties of the Fast Outflow of APM 08279+5255

APM 08279+5255 is a gravitationally lensed BAL quasar at redshift \( z = 3.911 \) (Downes et al. 1999). Its bolometric luminosity estimated as \( L_{\text{bol}} = 7 \times 10^{15} \mu _L^{-1} L_\odot \) (\( \mu _L \) is the lens amplification factor; Irwin et al. 1998; Riechers et al. 2009) makes this source one of the most luminous in the universe,\(^6\) despite the value of the lens amplification factor. The presence of high-ionization BAL features produced in C IV, O vi, N v, and Ly \( \alpha \) transitions indicates that it is a high-ionization BAL quasar (HiBAL). The C IV BAL of APM 08279+5255 contains multiple absorption troughs with widths ranging between 2000 km s\(^{-1}\) and 2500 km s\(^{-1}\). The maximum observed outflow velocity of the C IV absorption is \( v_{\text{max(CIV)}} \sim 0.04c \) relative to the source systemic redshift of \( z = 3.911 \) (Srianand & Petitjean 2000).

Gravitational lensing of APM 08279+5255 produces three images with the two brightest ones separated by \( \sim 0.5'' \) (see Figure 1). The time delay between images A and B of APM 08279+5255 is estimated to be of the order of a few hours (e.g., Muñoz et al. 2001). The Eddington ratio of APM 08279+5255 can be estimated from an assumed value of \( \Gamma \sim 2 \) (where \( \Gamma \) is the X-ray photon index), which is close to the mean value estimated from observations (Saez et al. 2009; Chartas et al. 2009b), and using the \( L_{\text{bol}}/L_{\text{Edd}} \) versus \( \Gamma \) correlation found in RQ quasars (e.g., Wang et al. 2004; Shemmer et al. 2006, 2008). The \( L_{\text{bol}}/L_{\text{Edd}} \) versus \( \Gamma \) correlation for APM 08279+5255 implies \( L_{\text{bol}}/L_{\text{Edd}} \sim 0.2 \), and therefore \( M_{\text{BH}} \sim 10^{12} \mu _L^{-1} M_\odot \). A second independent method of estimating the Eddington ratio through the use of the observed width of the C IV line indicates a black hole mass of \( M_{\text{BH}} \sim 10^{11} \mu _L^{-1} M_\odot \) (see, e.g., Riechers et al. 2009). The Eddington ratio derived using the second method is \( L_{\text{bol}}/L_{\text{Edd}} \sim 2 \), implying that the source is accreting at a super-Eddington rate. However, caution must be taken with this result because the estimates of \( M_{\text{BH}} \) based on C IV emission-line widths are subject to a lot of systematic uncertainties (i.e., it contains non-virial components such as the disk wind that can contribute to the broadening, e.g., Shemmer et al. 2008). There are also conflicting reported estimates of the magnification parameter (\( \mu _L \)). Optical observations indicate \( \mu _L \sim 100 \) (e.g., Egami et al. 2000), while observations of CO emission yield \( \mu _L \sim 4 \) (e.g., Riechers et al. 2009). In this work we try, as far as possible, to present our results as a function of the magnification factor, however when this is not possible a value of \( \mu _L = 100 \) is assumed (as in Egami et al. 2000). The absorption corrected optical to X-ray power-law slope\(^7\) of APM 08279+5255 is \( \alpha _{\text{ox}} \sim -1.8 \) (e.g., Dai et al. 2004). The relatively soft SED of APM 08279+5255 combined with its nearly large Eddington ratio provides ideal conditions for the production of radiatively driven winds (see, e.g., Everett 2005; Section 4).

2.2. Results from Eight Deep X-ray Observations of APM 08279+5255

This section summarizes results from two Chandra, three XMM-Newton, and three Suzaku observations of APM 08279+5255 (eight in total; see Table 1 for details). The data reduction of the Chandra and XMM-Newton observations is described in Chartas et al. (2009b) and the reduction of the

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\(^5\) The commonly used definition of BAL quasar (i.e., Weymann et al. 1991) does not consider outflow velocities \( > 25,000 \text{ km s}^{-1} \). A BAL wind has also been found in the X-ray band (Chartas et al. 2002, 2007b), however, the X-ray faintness of BAL quasars (Gallagher et al. 2006) has limited the number of cases with observed X-ray BALs to a few.

\(^6\) As a reference the most luminous quasars in the Sloan Digital Sky Survey have \( L_{\text{bol}} \sim 10^{11} L_\odot \) (e.g., Ganguly et al. 2007).

\(^7\) \( \alpha _{\text{ox}} \) is defined as the slope of a hypothetical power law extending between 2500 \( \AA \) and 2 keV in the AGN rest frame, i.e., \( \alpha _{\text{ox}} = \log _{10} \frac{F_{\nu}(2 \text{ keV})}{F_{\nu}(2500 \text{ \AA})}/\log _{10} \frac{\nu_{2500}}{\nu_{2 \text{ keV}}} \sim 0.383 \log \frac{\nu_{2500}}{\nu_{2 \text{ keV}}} \).

\(^8\) The \( \alpha _{\text{ox,UV}} \) relation described in Strateva et al. (2005) and Steffen et al. (2006) predicts that \( \alpha _{\text{ox,UV}} = (-0.137 \pm 0.008) \log _{10} \frac{L_{\nu}(2500 \text{ \AA})}{L_{\nu}(2.36 \text{ keV})} + 2.638 \pm 0.240 \).

Using the Irwin et al. (1998) work, we estimate that \( \log L_{\nu}(2500 \text{ \AA}) \sim 31.7 \) (\( \mu _L \sim 100 \)) and therefore we obtain \( \alpha _{\text{ox,UV}} \sim -1.7 \pm 0.3 \) in accordance with the Dai et al. (2004) value.
Figure 1. Deconvolved image (left panel) of the 2002 February 24 Chandra observation of APM 08279+5255. North is up and east is to the left. Best-fit point spread function (PSF) model (right panel) to the same observation of APM 08279+5255. (A color version of this figure is available in the online journal.)

Table 1

| Datea | OBS ID   | Telescope | Instrument | Exposure | Net Exp | Net Counts | f_0.5−8 |
|-------|----------|-----------|------------|----------|---------|------------|---------|
| 2002 Feb 24 (Epoch 1) | 2979 | Chandra | ACIS BI | 91.9 ks | 88.8 ks | 5.627 ± 75 | 5.44 ± 0.15 |
| 2002 Apr 28 (Epoch 2) | 0092800201 | XMM-Newton | EPIC pn | 102.9 ks | 83.5 ks | 12,820 ± 139 | 5.51 ± 0.15 |
| 2006 Oct 12 (OBS1) | 701057010 | Suzaku | XIS FI | 102.3 ks | 71.3 ks | 2,325 ± 64 | 5.39 ± 0.43 |
| 2006 Oct 12 (OBS1) | 701057010 | Suzaku | XIS BI | 102.3 ks | 71.3 ks | 2,325 ± 64 | 5.39 ± 0.43 |
| 2006 Nov 1 (OBS2) | 701057020 | Suzaku | XIS FI | 102.3 ks | 67.9 ks | 5498 ± 87 | 5.18 ± 0.32 |
| 2006 Nov 1 (OBS2) | 701057020 | Suzaku | XIS BI | 102.3 ks | 67.9 ks | 2,181 ± 62 | 5.15 ± 0.37 |
| 2007 Mar 24 (OBS3) | 701057030 | Suzaku | XIS FI | 117.1 ks | 86.4 ks | 4750 ± 80 | 5.55 ± 0.49 |
| 2007 Mar 24 (OBS3) | 701057030 | Suzaku | XIS BI | 117.1 ks | 86.4 ks | 2,918 ± 71 | 5.63 ± 0.39 |
| 2007 Oct 6 (Epoch 3) | 0502220201 | XMM-Newton | EPIC pn | 89.6 ks | 56.4 ks | 11,400 ± 114 | 6.04 ± 0.16 |
| 2007 Oct 22 (Epoch 4) | 0502220301 | XMM-Newton | EPIC pn | 90.5 ks | 60.4 ks | 16,698 ± 133 | 8.06 ± 0.15 |
| 2008 Jan 14 (Epoch 5) | 7684 | Chandra | ACIS BI | 91.7 ks | 88.06 ks | 6,938 ± 83 | 5.89 ± 0.21 |

Notes.
a The date are also described by the term in parentheses.
b Background-subtracted source counts including events with energies within the 0.2–10 keV band. See Section 2 of Chartas et al. (2009b) and Section 2 of Saez et al. (2009) for details on source and background extraction regions used for measuring N_{src}.
c The fluxes (in units of 10^{-13} erg cm^{-2} s^{-1}) in the 0.5–8 keV observed-frame band are obtained using the best-fit absorbed power-law model with two absorption lines. The details of these fits are presented in Table 3 of Saez et al. (2009) and in Table 2 of Chartas et al. (2009b). The fluxes have been corrected for Galactic absorption.

Our analysis of the X-ray observations of the BAL quasar APM 08279+5255 indicates strong and broad absorption at rest-frame energies of 1–4 keV (low-energy) and 7–18 keV (high-energy). The medium producing the low-energy absorption is a nearly neutral absorber with a column density of log(N_H/cm^{-2}) ∼ 23. However, since APM 08279+5255 is at a high redshift of z = 3.91 it is difficult to constrain the ionization state of the low-energy absorber. The absorption signatures of this complex low-energy absorber are shifted outside the range of the observed X-ray band (typically between 0.3 and 10 keV). The high-energy absorption features are easily detected in the eight deep X-ray observations of APM 08279+5255. In every case these features satisfy EW/σ_{EW} > 3 (see Saez et al. 2009; Chartas et al. 2009b), and therefore they satisfy realistic limits for significant detections (Vaughan & Uttley 2008).

Chartas et al. (2002) have interpreted the high-energy X-ray BALs as being produced by absorption of highly ionized iron such as Fe.xxv Kα (1s^2 − 1s2p; 6.70 keV) and/or Fe.xxvi (1s − 2p; 6.97 keV) launched very near an ionizing compact central source. Evidence to support this interpretation is the significant variability in the strength and energy of the X-ray

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EW is the equivalent width obtained using the best-fitted model of the high-energy absorption feature. The equivalent width (EW) is defined as 

\[ EW = \int \frac{F_c - F_e}{F_c} dE, \]

where F_c is the continuum flux and F_e is the flux in the absorber.
BALs over short timescales present in many of the observations. This variability is found to be as short as ~3 days rest frame in the *Chandra* and *XMM-Newton* observations, and ~month in the *Suzaku* observations. This fast variability presents a strong argument in favor of a wind that originates from a distance of a few times the Schwarzschild radius.10

In the *Suzaku* observations, the variability of the high-energy absorber is present at energies close to 7 keV rest frame. On the other hand, the *Chandra* and *XMM-Newton* observations show variability of the high-energy absorption profiles at both low energies (i.e., rest-frame energies ~7 keV) and high energies (i.e., rest-frame energies ~10 keV). A time-variable outflow provides a plausible explanation for the changes in shape on the absorption features in past X-ray observations of *APM 08279+5255* (Chartas et al. 2002; Hasinger et al. 2002). An even stronger case is presented in Chartas et al. (2009b) and Saez et al. (2009), where it can be seen clearly that in some cases the appearance of the high-energy absorption feature can take the shape of a notch, an edge or two absorption lines. Our spectral analysis of the eight deep observations also indicates variability of the parameters defining the high-energy attenuation which is likely due to a change in the outflow velocity of the absorber (Saez et al. 2009; Chartas et al. 2009b). The short timescale (~week in the rest frame) of the variability combined with the high ionization of the absorbing material which is moving at relativistic speeds implies that the absorbers are launched from distances ~10*R*S from the central source (see, e.g., Section 4 of Saez et al. 2009). The short timescale of this variability in the *Suzaku* (Saez et al. 2009) and *XMM-Newton* (Chartas et al. 2009b) observations also indicates that this absorber should be strongly accelerated. The global covering factor of these winds should be low ~<20% based on the absence of emission features from the outflowing ionized gas (see, e.g., Chartas et al. 2009b).

The minimum and maximum projected velocities (*v*<sub>min</sub>, *v*<sub>max</sub>) of the outflow are estimated from the minimum and maximum energy ranges (*E*<sub>min</sub>, *E*<sub>max</sub>), respectively, of the high-energy absorption features in *APM 08279+5255*. We obtained *E*<sub>min</sub> and *E*<sub>max</sub> from our spectral fits assuming first the two absorption line (APL+2AL) models. Specifically, based on the best-fit values of an absorbed power-law model with two absorption lines (from Table 3 of Saez et al. 2009 and Table 2 of Chartas et al. 2009b), we obtain *E*<sub>min</sub> = *E*<sub>abs1</sub> - 2σ<sub>abs1</sub> and *E*<sub>max</sub> = *E*<sub>abs2</sub> + 2σ<sub>abs2</sub>. As in Chartas et al. (2009b), we estimate the line-of-sight-projected velocities *v*<sub>min</sub> and *v*<sub>max</sub> assuming that the absorption arises from highly blueshifted Fe xxv Kα (*E*<sub>lab</sub> = 6.7 keV). In Table 2, we also add a column with the fitted values of *Γ* (based on the APL+2AL model). Using *E*<sub>max</sub> ~ 18 keV (the maximum observed value), we constrain the maximum angle11 between our line of sight and the wind direction to be less than 22°.

As we indicated in Chartas et al. (2009b) and from Table 2, there is a hint that changes in the photon index (*Γ*) may be positively correlated with the changes of the maximum velocity of the outflow (*v*<sub>max</sub>). This possible trend between *Γ* versus *v*<sub>max</sub> is shown in Figure 10 of Chartas et al. (2009b). In Section 3, we reevaluate the velocities found in Table 2 with a model based on *CLOUDY* simulations of a near-relativistic outflow. In Section 4, we provide an interpretation of the possible trend between maximum outflow velocity and *Γ*.

### 3. PHOTOIONIZATION MODELS OF NEAR-RELATIVISTIC OUTFLOWS

#### 3.1. Motivation

From the X-ray analysis of our eight observations of *APM 08279+5255* (see Saez et al. 2009; Chartas et al. 2009b for more details), and past observations of this object and PG 1115+080 (e.g., Chartas et al. 2007a), it became clear that a more sophisticated spectral model was needed to fit the X-ray BALs. Currently, there are no proper tools available in the spectral fitting package *xspec* to model absorption profiles resulting from near-relativistic outflows. In Saez et al. (2009), we used photoionization models created from the photoionization

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10 The timescale of the flux variability provides an indication of the outflow launching radius from the central engine (see, e.g., Saez et al. 2009). The size of this region should be approximately the timescale of the variability times the speed of light. Variability over a period of a ~week implies a launching radius ~ R*S. In the last expression, we estimated the Schwarzschild radius (R*S) of *APM 08279+5255* using M*~10*9M⊙ (obtained assuming μ<sub>LS</sub> ~ 100; see Section 2.1). Possible flux variability caused by the time delay between the images is shorter than R*S/c.

11 The Doppler-shift formula predicts that given a fixed ratio of *E*<sub>obs</sub>/E<sub>obs</sub> = R<sub>b</sub> (where *E*<sub>obs</sub> and E<sub>obs</sub> are the energy of the absorption line in the rest frame and observed frame, respectively) the maximum angle between our line of sight and the wind direction is given by θ<sub>max</sub> = cos<sup>−1</sup>(√1 - R<sub>b</sub>)).
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code xstar (see, e.g., Kallman & Bautista 2001) to fit the broad absorption feature found between 7 and 18 keV rest frame in APM 08279. This spectral analysis did not include relativistic corrections and does not contain a realistic model of the outflow. In this section, we describe new software code that we have developed that provides a more realistic description of radially accelerated near-relativistic outflows. Our main goal is to better constrain important parameters describing near-relativistic outflows; among these are the velocity profile, the ionization parameter, and the column density of the observed X-ray wind.

3.2. Description of the Code

Our quasar outflow code is based on a multilayer approach which mimics the absorption and scattering through a near-relativistic outflow using the photoionization code CLOUDY (Ferland et al. 1998). An existing quasar outflow code called xscort developed by Schurch & Done (2007) follows a similar approach and is based on the photoionization code xstar.

In our quasar outflow code, we use CLOUDY simulations to approximate the absorption signature produced by an outflowing medium that is radiatively accelerated from a central source. We describe the outflowing medium with a set of absorption layers with specific velocity profile and ionization states. The details of the approximations and assumptions used in our quasar-outflow model are described in the following paragraphs.

3.2.1. The Case of One Absorption Layer

We approximate the attenuation through the outflowing ionized gas as the absorption through a series of layers of different velocities and ionization states. We begin by calculating the output absorption profile assuming the wind is made up of a single layer and then generalize our model by dividing the outflowing wind into multiple layers. We assume that the layer is at a distance \( R \) from the continuum source, has a thickness \( \Delta R \), a density \( n \), and is moving at a velocity \( v \) away from it. We further assume that SED of the source is a power law \( (L_\nu \propto \nu^{\alpha}) \) with spectral index \( \alpha = -1.0 \). From here on, unless mentioned otherwise, this is the SED that we will assume in our simulations. The ionization parameter \( \xi \) measured in the absorption layer’s rest frame is

\[
\xi = \frac{4\pi F_\nu}{n} \tag{1}
\]

where primed quantities \( n' \) \( (n' = \gamma n) \) and \( F_\nu \) refer to the density and the incident ionizing flux in the layer’s rest frame, respectively. Non-primed parameters are assumed to be in the rest frame of the luminous source. Using the fact that \( I_\nu/v^3 \) is a Lorentz invariant, the incident ionization flux in a layer’s rest frame is given by

\[
F_\nu = \gamma^4 (1 - v/c)^4 F_1 \tag{2}
\]

Since \( F_1 \propto I_\nu, v/v' = D, \) where \( D = \gamma^{-1}(1 - v/c)^{-1} \) and \( I_\nu = I_\nu/v^3/v' = I_\nu/D^3 \). Therefore,

\[
F_\nu' = \int_0^\infty F_\nu dv' = D^4 \int_0^\infty F_\nu dv, \]

where \( v_0' = 1 \) Ry and \( v_1' = 1000 \) Ry. \( v_0' = D v_0' \). Conversely, to calculate the incident flux in the layer’s rest frame, we integrate the flux in the luminous source rest frame and multiply by a factor of \( D^{-4} \). Note that if the flux is a power law, i.e., \( F_\nu = av^\alpha \), then \( F_\nu' = aD^{-4}(v/v_0')^\alpha \) if \( \alpha = -1 \), and

\[
F_\nu' = aD^{-4}(v/v_0')^\alpha(v/v_0')^{-1}(v_0' + 1)\Gamma(\alpha + 1) \]

if \( \alpha 
eq -1 \). Therefore in the case that the SED is a power law, the ionizing flux in the rest frame of the absorbing layer can be found by integrating the flux in the luminous source rest frame between 1 Ry and 1000 Ry, and then multiply by \( D^4 \), where \( \alpha \) is the spectral index.

The column density \( N_\text{HI} \) of the layer is given by \( N_\text{HI} = n\Delta R \). The incident flux on a layer is calculated between 1 and 1000 Ry in the rest frame of the moving layer. From the incident flux in the rest-frame of the layer and from the use of Equation (1), we calculate the ionization state of this layer. We next input the derived ionization state and column density of the layer into the photoionization code CLOUDY to obtain the output spectrum of the layer in its rest frame and transform it to the rest frame of the luminous source.

3.2.2. A Model to Describe X-Ray Absorption Profiles

The X-ray spectra that we have obtained from observations of several BAL quasars do not show any emission lines associated with the X-ray BALs (Chartas et al. 2009b). This is expected since BAL quasar outflows in general have relatively small global covering factors (Hewett & Foltz 2003). Therefore, we will concentrate on absorption-dominated outflows neglecting emission features in our model. For our CLOUDY code, we will assume an approximately constant ionization parameter in the outflow.

We assume that the region of the outflow that contributes to the observed Fe xxv and/or Fe xxvi absorption is localized in a relatively thin multilayer of thickness \( \Delta R \) at a distance \( R \) from the black hole. The justification behind the assumption that \( \Delta R \ll R \) in our model is that the presence of Fe xxv is likely to occur in a relatively narrow region away from the source where the ionization parameter and density are such that Fe xxv is abundant at these distances. Even though the ionization parameter is expected to fall off with distance along the flow as \( 1/R^2 \) it remains relatively constant within the multilayer since \( \Delta R \ll R \). To compensate for changes in flux across the multilayer due to relativistic effects (e.g., beaming effects), we adjust the density \( n_i \) of each layer such that the ionization parameter remains approximately constant within the multilayer \( \Delta R \). In the case that the region of the outflow that we are modeling is not physically thin, our approach will still be valid as long as the ionization parameter along this region does not change appreciably.

From Equation (1), the ionization parameter of each layer is

\[
\xi_i = 4\pi F_\nu_i/v_i \tag{3}
\]

where \( F_\nu_i \) is the incident flux in the rest frame of layer \( i \) estimated from the flux coming from layer \( i-1 \) after taking into account relativistic effects. The density of each layer is determined from an a priori defined velocity profile \( v(r) \). In our multilayer approach, the density of each layer is

\[
\xi_i = (1 - v_i/v_0')^4 \tag{4}
\]

where

\[
N_i = n_i \Delta R_i, \quad \Delta R_i = n_i v_i \Delta R, \quad n_i v_i \Delta R_i = \frac{\xi_i}{4\pi} \tag{5}
\]

These relations mean that the ionization parameter with typical value of \( \log \xi \approx 15 \) in our simulations is \( N_i \approx 10^{22} \text{ cm}^{-2} \).

The Rydberg is a unit of energy defined in terms of the ground-state energy of an electron for the hydrogen atom, 1 Rydberg \( \approx 6e \text{ V} \).

14 The Rydberg is a unit of energy defined in terms of the ground-state energy of an electron for the hydrogen atom, 1 Rydberg \( \approx 13.6 \text{ eV} \).

15 In our simulations, we assume that the ionization luminosity is \( L_1 = 10^{45} \text{ erg s}^{-1} \), therefore for a layer with \( \log \xi = 3.0 \), \( n = 10^{12} \text{ cm}^{-3} \) (initial density assumed in our runs, see Section 3.2.4), and \( \log(N_\text{HI}/\text{cm}^{-2}) = 23 \), we will typically have that the ratio of thickness to distance of the layer is \( \Delta R/R \approx 0.001 \) and consequently \( \Delta R_i \approx 2 \). This means that the ionization parameter with typical value of \( \log \xi \approx 3 \) varies through the outflow \( \approx 100 \text{ dex} \) due to the radial dependency.

16 We use \( \approx 100 \) layers to generate the absorption profile of a simulated wind, therefore each layer has a column density of \( \log(N_\text{HI}/\text{cm}^{-2}) \lesssim 22 \).
it can be assumed to be almost transparent (or thin) to radiation (see Appendix A.2). As we describe in Section 3.2.3, the assumption of optically thin layers will allow us to more greatly reduce the time needed to compute the absorption signature of the multilayered outflow.

In this work, we assume that the outflow velocity profile will have a $p$-type form given by

$$v(N_H) = v_{\text{min}} + (v_{\text{max}} - v_{\text{min}})(N_H/N_{\text{H}})^p,$$  \hspace{1cm} (3)

where $N_H$ is the total column density of the simulated wind ($0 < N_H < N_{\text{H}}$). We note that given the assumptions described here, and the moderate $S/N$ of the absorption profile in X-ray, we do not expect to obtain significant constraints on the acceleration mechanism of the outflow by using this profile.

3.2.3. Passing a Continuum Spectrum from One Absorbing Layer to the Next

When passing the continuum spectrum from one layer ($i$-1) to the next ($i$), we first transform the source rest-frame spectrum coming from layer $i$-1 to the rest frame of layer $i$. In the rest frame of layer $i$, we remove absorption and add emission (in cases where we do consider emission) to the incident spectrum given the column density and ionization parameter of the layer. The column density of layer $i$ is obtained from the velocity profile, and its ionization parameter is calculated from the input spectrum in its rest frame. Finally, we transform the output spectrum coming from layer $i$ back to the source rest frame.

Since the density of each layer is chosen to correct the attenuation of the flux due to relativistic effects, the ionization parameter will mostly decrease due to the absorption of the outflow across the layer. The decrease of the ionization through the multilayered outflow due to absorption will be greater in winds that are less ionized and with higher column densities. For example, a wind with $\log(N_H/\text{cm}^{-2}) = 22.75$ with initial ionization parameter of $\log(\xi) = 3.25$ will have a final ionization parameter of $\log(\xi) \sim 3.21$, however for $\log(N_H/\text{cm}^{-2}) = 22.75$ and $\log(\xi) = 3.75$ the final ionization parameter is $\log(\xi) \sim 3.73$. Additionally, a wind with $\log(N_H/\text{cm}^{-2}) = 23.75$ and $\log(\xi) = 3.25$ will have $\log(\xi) \sim 2.84$, however if $\log(N_H/\text{cm}^{-2}) = 23.75$ and $\log(\xi) = 3.75$ then $\log(\xi) \sim 3.53$.

After correcting the spectrum incident on layer $i$ for the effects of relativistic beaming, we estimate the absorption and emission from layer $i$ using simulations performed with the photoionization code Cloudy. These cloudy simulations are implemented using the unabsorbed source spectrum (power law with $\alpha = -1$ in our case) and various values of the ionization parameter. The main advantage of this approximation is a dramatic shortening in the time it takes to obtain a profile. This speed-up is possible because the photoionization runs at each layer use a library of preexisting cloudy runs (see the next paragraph for details). If the flux emitted by the source is a power law, the flux received by a moving layer is also a power law with the same spectral index as the source as long as the SED is not significantly attenuated in an energy-dependent way. In addition, if each layer of the multilayered media is approximately optically thin then the state of the gas depends primarily on the ionization parameter and secondarily on the SED (Tarter et al. 1969). This dependence indicates that our approach is at first order a good approximation as long as the SED along the multilayered outflow does not differ appreciably from the incident SED at the first layer. However, for low ionization states ($\log(\xi) < 3$) and large total column densities ($\log(N_H/\text{cm}^{-2}) \gtrsim 23.5$), the SED along the multilayered outflow will deviate appreciably from the initial incident SED, and therefore, our approximation breaks down.

In order to avoid invoking cloudy too many times (~100) to simulate the signature of the multilayered absorber, we created a library of spectra to speed up our calculations. This library contains a set of simulated transmitted spectra through absorbers having a range of ionization parameters between 1.8 and 4.1 dex ($\log(\xi)$ steps of 0.01 dex), column density of $\log(N_H/\text{cm}^{-2}) = 19$, density of $n_H = 10^{12} \text{cm}^{-3}$, and an input SED that has the form of a power law ($L_\nu \propto \nu^\alpha$) in the energy range between 1 and $10^4$ Rys with spectral index $\alpha = -1$. The value of the density of the absorber ($n_H = 10^{12} \text{cm}^{-3}$) is chosen to be close to the value of the density predicted by two-dimensional numerical simulations of radiative winds by Proga et al. (2000) and Proga & Kallman (2004). The simulations used to construct this library (from here on referred to as library runs), as well as all the simulated profiles described in the next sections, are calculated using standard solar metallicities. We primarily used cloudy to perform the photoionization calculations but we also compared our results with those generated by the photoionization code xstar.

In order to reduce the number of realizations in our library, we performed these runs assuming a specific turbulent velocity of $v_{\text{turb}} = 15000 \text{km s}^{-1}$. Our choice of a specific turbulent velocity requires that the relative speed $\Delta v_i'$ between layers $i$ and $i + 1$ to be the same for every layer in the simulations of multilayered outflows (i.e., $\Delta v_i' = \Delta v'$; see Appendix A.3). In our simulations, we use a finite number of layers to describe the outflow, each layer having a slightly different velocity following the adopted velocity profile. The distribution of the velocity differences between adjacent layers is assumed to be uniform and to extend between 0 and a maximum velocity difference of $\Delta v'$. The velocity difference of $\Delta v'$ is kept lower than $v_{\text{turb}}\sqrt{\Delta z}$, where $v_{\text{turb}} = 15000 \text{km s}^{-1}$ is the assumed turbulent velocity (see Schurch & Done 2007). By selecting a turbulent velocity we set a lower limit on the number of layers used in simulating a BAL spectrum. The simulations making up our library are all performed using the same column density ($\log(N_H/\text{cm}^{-2}) = 19$). Consequently, the opacity of a layer $i$ (i.e., the layer’s rest-frame absorption) is calculated by first obtaining the opacity from the library at the ionization state of the layer and second by scaling the opacity obtained (from the library) to the column density of the layer. This approximation is justified given that in the range of densities of our simulations ($8 \lesssim \log n_H \lesssim 12$) the dependency of the opacity on $n_H$ is negligible, and therefore, the opacity of a layer $i$ can be found from the library just by knowing its ionization state and column density. Emission spectra may also be obtained from our library runs, however for our study we mostly concentrated on the absorption spectra. We focus on the absorption spectra since the main goal of our study is to fit the spectral signatures produced by winds in which emission lines are relatively weak implying

17 The relative velocities of two adjacent layers according to special relativity are $\Delta v_i' = (v_{i+1} - v_i)/(1 - v_{i+1}/c^2)$.
18 For example, if the velocity profile has $v_{\text{min}} = 0$ and $v_{\text{max}} = 0.7c$ we require that the number of layers $N_l > (v_{\text{max}} - v_{\text{min}})/\sqrt{\Delta z v_{\text{turb}}}$, i.e., with $v_{\text{turb}} = 15000 \text{km s}^{-1}$, the minimum number of layers that we can use for this case is 40.
19 For thin layers, the opacity of a layer ($\tau_l$) can be obtained by scaling the opacity of a different layer ($\tau_{l2}$) by the ratio of the column densities of the two layers (i.e., $\tau_l = \tau_{l2}N_{l2}/N_{l1}$).

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low global covering factors. Additionally, we assume that the line-of-sight covering factor is equal to one.

3.2.4. Testing Our Relativistic Outflow Code

We first generate the absorption profiles for a linearly accelerated outflow with $v_{\text{min}} = 0$, $v_{\text{max}} = 0.3c$ ($v \propto N_{\text{HI}}$), $N_{\text{HI}} = 3 \times 10^{23} \text{ cm}^{-2}$, initial density $n_0 = 10^{12} \text{ cm}^{-3}$, and values of $\log \xi = 2.75, 3.00, 3.25, 3.50, 3.75$, and $4.00$. These profiles have been generated to compare the results of our code with those presented in Schurch & Done (2007). In order to make a fair comparison with the results of Schurch & Done (2007), we use a library of XSTAR runs using a power-law model with $\alpha = -1.4$. This library of XSTAR runs has the same characteristics as the CLOUDY library described in Section 3.2.3. Our simulated X-ray absorption profiles are very similar to the ones computed by Schurch & Done (2007) under the assumption of a multilayered outflow with spherical symmetry (see Appendix A.4).

We generate a second run of simulations based on our results presented in Section 2.2. For this purpose, we simulate absorption profiles with $v_{\text{min}} = 0.1c$, $v_{\text{max}} = 0.7c$, $n_0 = 10^{12} \text{ cm}^{-3}$, $\log(N_{\text{HI}}/\text{cm}^{-2}) = 23.75$, and three values of the ionization parameter $\log \xi = 3.0, 3.5, \text{ and } 4.0$. The output profiles have been chosen approximately in accordance to the estimated values based on one of the XMM-Newton observations of APM 08279+5255 (Epoch 3 from Chartas et al. 2009b). To generate notch-type absorption profiles, we chose $p = 1$ for these simulations. The resulting profiles are presented in Figure 2. In Figure 3, we zoom in on the iron blend feature which shows up at energies between 7.5 and 16.5 keV. The resonance absorption lines responsible for the features are mainly Fe XXV Kα (1s$^2$ - 1s 2p; 6.70 keV) and Fe XXVI Kα (1s$^2$ - 2p; 6.97 keV). From Figures 2 and 3, it is clear that the strength of the iron blend feature is larger for $\log \xi = 3.5$. The strength of this feature is large for ionization parameters in the range of $3 \lesssim \log \xi \lesssim 4$, since at lower ionization levels the abundance of highly ionized iron atoms (e.g., Fe XXV and Fe XXVI) is too small to produce any appreciable feature in the spectra. At $\log \xi \gtrsim 4$ the atoms in the gas become stripped of almost all their electrons, and therefore, the resulting spectra contain very few bound–bound and bound–free absorption features. When $\log \xi \lesssim 3$ there is substantial absorption present at rest-frame energies $\lesssim 2$ keV. As a consequence, in a heavily absorbed source like APM 08279+5255, the low-energy ($\lesssim 2$ keV) absorbed component of the spectrum, possibly due to non-outflowing material, will overlap with the absorbed component produced by the wind (e.g., Saez et al. 2009; Chartas et al. 2009b). However, the high-energy absorption iron trough (above $\sim 7$ keV) is not contaminated by absorption lines from non-outflowing material, and consequently, it provides a clean signature of the outflowing material.

The absorption profiles described in Section 2.2 contain a diversity of shapes, sometimes resembling notches, edges, or two absorption lines. Given the variety of shapes of the absorption profiles, we attempted to emulate these different shapes by generating simulations of outflows with $v_{\text{min}} = 0.1c$ and $v_{\text{max}} = 0.7c$, $\log(N_{\text{HI}}/\text{cm}^{-2}) = 23.75$, $\log \xi = 3.5$, and three values of $p$, $p = 0.5, 1$, and 2. The output spectra of the resulting velocity profiles (see Figure 4) are presented in Figure 5. In the lower panel of Figure 5, we also show as a reference three model spectra used to fit Epoch 3. The three different models used are a notch, an edge, and a two-absorption line model (see Table 2 from Chartas et al. 2009b).

3.3. Fits to the Observed Spectra of APM 08279+5255 Using Our Quasar Outflow Model

In this section, we present results from fits to spectra obtained from XMM-Newton, Chandra, and Suzaku observations of APM 08279+5255 using our thin multilayered outflow model. We created xspec model tables from the CLOUDY output of the simulations covered five important properties of the multilayered outflow model: minimum velocity of the outflowing gas $v_{\text{min}}$, maximum velocity $v_{\text{max}}$, ionization parameter $\xi$, total column density $N_{\text{HI}}$, and the value $p$ which defines the outflow velocity profile (see Equation (3)). For our simulations, we assume

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20 A table model consists of a file that contains an $N$-dimensional grid of model spectra with each point on the grid having been calculated for particular values of the $N$ parameters in the model. xspec will interpolate on the grid to get the spectrum for the parameter values required at that point in the fit.
assumed that the outflow has a launch velocity of 0.1 \( c \) (Equation (3)), for three different values of the exponent of the outflowing gas in the multilayer of the outflowing black hole, with a thickness \( R_i \) from the black hole, with a thickness \( \Delta R_i (\Delta R_i/R_i \ll 1) \), a velocity gradient of \( \Delta v \) across it, a column density of \( N_H \), and an ionization parameter of \( \log \xi \). We produced the table model \texttt{windfull.tab} by simulating transmitted spectra through a range of outflows with minimum velocities \( v_{\text{min}} \) in the range of 0.0–0.3c (a simulation for every 0.02c interval), with maximum velocities \( v_{\text{max}} \) in the range of 0.3–0.9c (step intervals of 0.04c), \( \log(N_H/\text{cm}^{-2}) \) in the range 22–24 (step intervals of 0.25 dex), and the index \( p \) having values of 0.5, 1.0, 2.0, and 5.0.

In several observations, the X-ray BALs produced by highly ionized iron lines (above 7 keV rest frame) appear to consist of two broad absorption components. The component covering low energies (\( \lesssim 9 \) keV rest frame) is referred to as slow and the one covering larger energies (\( \gtrsim 10 \) keV rest frame) is referred to as fast. Typical models used to fit the fast component contain a number of Gaussian lines (Chartas et al. 2002, 2007a, 2009b; Saez et al. 2009). We created the table model \texttt{windvslow.tab} to fit the slow component and the table model \texttt{windvfast.tab} to fit the fast component. Since table models \texttt{windvslow.tab} and \texttt{windvfast.tab} are used to fit a relative small portion of the spectra we fix the velocity profile parameter to \( p = 1.0 \). Each component of the outflow has a velocity gradient \( \Delta v \) with a minimum \( v_{\text{min}} \) and maximum velocity \( v_{\text{max}} \) that satisfy \( v_{\text{max}} = v_{\text{min}} + \Delta v \). By fitting these table models to the spectra, we constrain the minimum and maximum projected velocities of each component. Table model \texttt{windvslow.tab} is generated with \( \Delta v \) having values in the range 0.02–0.42c (step intervals of 0.04c) and the parameters \( v_{\text{min}}, \log N_H, \) and \( \log \xi \) cover the same range and values as those used for producing table model \texttt{windfull.tab}.

3.3.3. \texttt{xspec} Table Models for Quasar Outflows

In order to fit the variety of absorption spectra of APM 08279+5255, we generated three different types of \texttt{xspec} table models that mainly differ in the parameter space of the outflow properties that are covered.

The first table model (\texttt{windfull.tab}) assumes the presence of only one outflowing component. We define as component \( i \) of an outflow a multilayer absorber at a distance \( R_i \) from the black hole, with a thickness \( \Delta R_i (\Delta R_i/R_i \ll 1) \), a velocity gradient of \( \Delta v \) across it, a column density of \( N_H \), and an ionization parameter of \( \log \xi_i \). We produced the table model \texttt{windfull.tab} by simulating transmitted spectra through a range of outflows with minimum velocities \( v_{\text{min}} \) in the range of 0.0–0.3c (a simulation for every 0.02c interval), with maximum velocities \( v_{\text{max}} \) in the range of 0.3–0.9c (step intervals of 0.04c), \( \log(N_H_i/\text{cm}^{-2}) \) in the range 22–24 (step intervals of 0.25 dex), and the index \( p \) having values of 0.5, 1.0, 2.0, and 5.0.

We fit the X-ray spectra of APM 08279+5255 using two different models. These two models assume a source spectrum consisting of a power law attenuated by Galactic absorption (\texttt{xspec} model \texttt{wabs}). We assumed a Galactic column density of 4.1 \( \times 10^{20} \) cm\(^{-2}\) (Kalberla et al. 2005). The first model (MODEL1) contains an intrinsic neutral absorber (\texttt{xspec} model \texttt{zwabs}) to describe the absorption in the low energy range of 1–4 keV rest frame and an outflowing ionized absorber (\texttt{xspec} table model \texttt{windfull.tab}) to account for the X-ray BALs. In \texttt{xspec} notation MODEL1 is written as \texttt{wabs*zwabs*mtab\{windfull.tab\}*pow}. The second model (MODEL2) contains an intrinsic neutral absorber (\texttt{xspec} model \texttt{zwabs}) to describe the absorption in the low energy range of 1–4 keV rest frame and a two-component outflowing ionized absorber (\texttt{xspec} table models \texttt{windslow.tab} and \texttt{windvfast.tab}) to account for the X-ray BALs. In \texttt{xspec} notation MODEL2 is written as \texttt{wabs*zwabs*mtab\{windslow.tab\}*mtab\{windvfast.tab\}*pow}.

We note that MODEL1 and MODEL2 use a neutral absorber to describe the intrinsic attenuation in the low energy range of 1–4 keV rest frame. In this work, we also tried fits with \( \Delta v \) having values in the range 0.02–0.42c (step intervals of 0.04c) and the parameters \( v_{\text{min}}, \log N_H, \) and \( \log \xi \) cover the same range and values as those used for producing table model \texttt{windfull.tab}.

3.3.2. Results from Fits to X-Ray Spectra of APM 08279+5255

![Figure 4](image-url) Figure 4. Outflow velocity as a function of column density through the outflow for three different values of the exponent of the p-type velocity profile (see Equation (3)), \( p = 0.5 \) (dotted line), 1.0 (solid line), and 2.0 (dashed line). We assumed that the outflow has a launch velocity of 0.1 \( c \), a terminal velocity of 0.7c, and a total column density of \( \log(N_H/\text{cm}^{-2}) = 23.75 \).

![Figure 5](image-url) Figure 5. Upper panel: X-ray spectra produced from multilayered \texttt{cloudy} simulations of near-relativistic outflows. The assumed input spectrum is a power law with \( \Gamma = 2.0 \) (solid line). The outflow has been accelerated between 0.1c and 0.7c using an exponent of the velocity profile with \( p = 1.0 \). The total column density of the outflow is \( \log(N_H/\text{cm}^{-2}) = 23.75 \). We have calculated the output spectra for three different values of the exponent \( p \), \( p = 0.5 \) (dotted line), 1.0 (solid line), and 2.0 (dashed line). Lower panel: X-ray spectra resulting from the best-fitted models used in Chartas et al. (2009b) to fit the high-energy absorption of APM 08279+5255 in Epoch 3. The solid line is for the notch model, the dotted line corresponds to the two absorption line model, and the dashed line is for the absorption edge model.
an ionized absorber to describe the attenuation at 1–4 keV; these fits did not result in a significant improvement over fits that used a neutral absorber. Additionally, as discussed in Saez et al. (2009) and Chartas et al. (2009b), the use of a neutral absorber to describe the absorption in the low energy range of 1–4 keV rest frame did not improve the use of more complex absorbers even for spectral fits performed to deep X-ray observations of APM 08279+5255. We also note that given the high redshift of APM 08279+5255, our fits to the spectra of this source cannot adequately constrain the low-energy intrinsic absorption.

For MODEL2, the current data cannot adequately constrain the ionization parameters of both the slow and fast components of the outflow. We therefore set the ionization parameters of the slow and fast component to be equal in MODEL2.\(^{21}\)

The results of the fits of these models to the Suzuki spectra of APM 08279+5255 are presented in Table 3 and to the Chandra and XMM-Newton spectra in Table 4. We note that in MODEL1 of Tables 3 and 4 log \(N_{\text{H}1}\) and log \(N_{\text{H}2}\) are the best-fitted column densities of the intrinsic neutral absorber and the outflowing ionized absorber, respectively. In MODEL2 of these same tables log \(N_{\text{H}1}\), log \(N_{\text{H}2}\), and log \(N_{\text{H}2}\) are the best-fitted column densities of the intrinsic neutral absorber, the slow and fast outflowing ionized absorber, respectively. In MODEL2 of these tables the velocity superscripts (1) and (2) represent the best-fitted velocity parameters of the slow and fast component, respectively.

In general, the models that fit the high-energy outflowing absorber (see Tables 3 and 4) tend to have ionization parameters in the range 3.2 ≤ log \(\xi\) ≤ 3.7. With the exception of the Chandra observations, there is no improvement in the fits when using MODEL2 over MODEL1. In Table 5, we show the statistical improvements based on the F-test of fits using MODEL2 over those using MODEL1. For the Chandra observations, the improvements are ≥99.5% when we use MODEL2 over MODEL1. There are also marginal improvements using MODEL2 over MODEL1 for the Suzuki observations especially in OBS1 (see Table 5). In general, we will use MODEL2 to estimate the outflow parameters because this model provides better constraints of the maximum velocity of the outflow. However, in the case of the XMM-Newton observations we use MODEL1 to estimate the outflow parameters because these observations show the widest X-ray BALs and provide better constraints.

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21 Note that in Saez et al. (2009) we tried a similar model to MODEL2 (model XSTAR4, Table 5 of the cited work) and found that the ionization state of the slow component could not be distinguished for the ionization state of the fast component in the Suzuki observations. We have a similar case when we try MODEL2 on our eight X-ray observations without setting the ionization parameter of the slow and fast component as equal.
Chartas et al. (2009b). We find a 0.04 ± 0.03 cm\(^{-2}\) between Epochs 1 and Epoch 5 when we plot the velocity of the slow component when we compare epochs and velocity of the slow component when we compare epochs OBS2 and OBS3. This overlap occurs in velocity space. This overlap occurs in velocity space.

Table 4

| Model | Parameter | Values Epoch 1 | Values Epoch 2 | Values Epoch 3 | Values Epoch 4 | Values Epoch 5 |
|-------|-----------|----------------|----------------|----------------|----------------|----------------|
| MODEL1... | \(\Gamma\) | 1.75 ± 0.03 | 2.00 ± 0.05 | 2.13 ± 0.09 | 2.38 ± 0.08 | 1.96 ± 0.03 |
| | log(\(N_{\text{H}}/\text{cm}^{-2}\)) | 22.67 ± 0.04 | 22.72 ± 0.04 | 22.71 ± 0.02 | 22.68 ± 0.02 | 23.02 ± 0.03 |
| | log(\(N_{\text{H}2}/\text{cm}^{-2}\)) | 23.62 ± 0.05 | 23.67 ± 0.06 | 23.76 ± 0.08 | 23.85 ± 0.06 | 23.13 ± 0.09 |
| | log \(\xi_2\) | 3.56 ± 0.08 | 3.35 ± 0.09 | 3.47 ± 0.10 | 3.36 ± 0.05 | 3.29 ± 0.12 |
| | \(v_{\text{min}}/c\) | 0.15 ± 0.01 | 0.13 ± 0.01 | 0.08 ± 0.02 | 0.05 ± 0.01 | 0.13 ± 0.03 |
| | \(v_{\text{max}}/c\) | 0.43 ± 0.03 | 0.64 ± 0.06 | 0.69 ± 0.03 | 0.73 ± 0.02 | 0.31 ± 0.02 |
| | \(p\) | 3.81 ± 0.12 | 2.2 ± 0.5 | 1.6 ± 0.2 | 1.5 ± 0.2 | 1 ± 0.4 |
| | log \(\chi_2\) | 46.83 ± 0.06 | 47.01 ± 0.07 | 47.15 ± 0.08 | 47.48 ± 0.12 | 46.91 ± 0.04 |
| | \(P(\chi_2^2/\nu)\) | 132.1 ± 104 | 110.5 ± 115 | 109.4 ± 105 | 152.4 ± 143 | 72.7 ± 70 |

Table 5

Estimates of the Improvement of Fits to the Spectra of APM 08279+5255 Using MODEL2 over MODEL1

| OBSID | Instrument | \(F\)-statistic | Null Probability | Significance |
|-------|------------|-----------------|-----------------|-------------|
| OBS1  | FI         | 2.59            | 4.8 ± 10\(^{-2}\) | 95.2%       |
| OBS1  | BI         | 3.05            | 1.5 ± 10\(^{-1}\) | 85.5%       |
| OBS2  | FI         | 5.32            | 2.4 ± 10\(^{-1}\) | 76.0%       |
| OBS2  | BI         | 7.15            | 1.4 ± 10\(^{-1}\) | 85.6%       |
| OBS3  | FI         | 1.31            | 2.8 ± 10\(^{-1}\) | 72.3%       |
| OBS3  | BI         | 1.91            | 1.6 ± 10\(^{-1}\) | 84.3%       |
| Epoch 1 | ACIS S3   | 6.68            | 1.8 ± 10\(^{-3}\) | 99.9%       |
| Epoch 2 | EPIC pn   | 1.56            | 2.2 ± 10\(^{-1}\) | 78.4%       |
| Epoch 3 | EPIC pn   | 1.40            | 2.5 ± 10\(^{-1}\) | 74.9%       |
| Epoch 4 | EPIC pn   | -               | -               | -           |
| Epoch 5 | ACIS S3   | 5.66            | 5.3 ± 10\(^{-3}\) | 99.9%       |

Notes.
- A MODEL1 is a power law with Galactic, neutral, and one-component outflow absorption (xspec model WABS*ZWABS*MTABLE {WINDFULL.TAB}*POW); MODEL2 is a power law with Galactic, neutral, and a two-component outflow absorption (xspec model WABS*ZWABS*MTABLE{WINDSLOW.TAB}*MTABLE{WINDFAST.TAB}*POW).
- The value on the left of the slash is the \(F\)-statistic and is given by \(F = \frac{\chi_2^2 - \chi_1^2}{\Delta}\). The value on the right of the slash represents the probability of exceeding the \(F\)-statistic based on the \(F\)-test.

Using either MODEL1 or MODEL2 we find a possible change in the maximum velocity of the outflow between the \textit{XMM-Newton} observations of Epoch 2 and Epoch 4, however, the significance of this change is only at the 1\(\sigma\) level (see Table 4). We do find significant changes in the minimum velocity and total column density of the outflow (log \(N_{\text{H}2}\); Table 4) between Epochs 2 and 4. In Table 4, we show that this variability is significant at the \(\gtrsim 2\sigma\) level for fits using...
MODEL1. In Figure 7, we plot confidence contours of log $N_{\text{H}_2}$ versus $v_{\text{min}}$ (left panel) and log $N_{\text{H}_2}$ versus $v_{\text{max}}$ (right panel) for each XMM-Newton observation for fits using MODEL1. We find that the significance of the variability between Epoch 2 and Epoch 4 of log $N_{\text{H}_2}$ versus $v_{\text{min}}$ is significant at the $\gtrsim 99.9\%$ level and of log $N_{\text{H}_2}$ versus $v_{\text{max}}$ is significant at the $\gtrsim 99\%$ level. We also find variability in the minimum velocity of the outflow when we compare Epoch 2 and Epoch 3. This can be seen in Table 4 and the left panel of Figure 7. From the confidence contours (Figure 7, left panel), we estimate the significance of the variability on log $N_{\text{H}_2}$ versus $v_{\text{min}}$ between Epoch 2 and Epoch 3 to be $\gtrsim 99\%$. It is worth mentioning that the fits using MODEL2 show an increase in the maximum velocity $\sim 2\sigma$ of the slow outflow component ($v_{\text{max}}^{(1)}$) between Epoch 3 and Epoch 4. This change is consistent with the change found in the first component energy of the two Gaussian absorption line model of Chartas et al. (2009b). Finally, we note that the spectral fits to the XMM-Newton observations show values of $\alpha$ that are greater than one. Although we find indications of variability of $\alpha$, these changes are not significant given the poor constraints of this parameter.

### 3.3.3. Mass Outflow Rate and Kinetic Energy of Outflow of APM 08279+5255

We use results from fits of our quasar-outflow model to the spectra of APM 08279+5255 to constrain the mass-outflow rate and kinetic energy injected by this outflow into the surrounding medium. In Saez et al. (2009) and Chartas et al. (2009b), we also constrained these properties of the outflow, however, these estimates were based on less realistic models (see Section 2.2).

A trend between $v_{\text{max}}$ and $\Gamma$ based on the X-ray observations of APM 08279+5255 was recently found by Chartas et al. (2009a). Such a trend is consistent with models that predict that quasar winds are driven by radiation pressure. Our fits with a more realistic quasar-outflow model confirm the trend between $v_{\text{max}}$ and $\Gamma$ (Figure 8, upper panel). We also find a possible trend between the total column density of the outflowing ionized absorber (log $N_{\text{H}_2}$) and $\Gamma$. As the lower panel of Figure 8 shows, we find that log $N_{\text{H}_2}$ increases with $\Gamma$. The increase of the maximum velocity with $\Gamma$ could be related to the fact that softer spectra have a stronger radiative effect on the wind (see Section 4; Section 3.3 of Chartas et al. 2009b). On the other hand, a possible increase in column density with $\Gamma$ could be indicating that APM 08279+5255 becomes a more effective radiative driving source as the spectrum of the ionizing source becomes softer. Additional X-ray observations of APM 08279+5255 will show if these trends are significant.

In order to calculate the mass-outflow rate ($M$) and the efficiency of the wind ($\epsilon_K$), we have modified the formulas used in Saez et al. (2009) and Chartas et al. (2009b) to include the modeled velocity gradient of the wind and include special relativistic corrections. The mass-outflow rate is given by

$$M = 4\pi f_c m_p R^2 \frac{\Delta R}{\Delta \rho} \int_0^{N_{\text{H}}} v(\hat{N}_H) d\hat{N}_H = 4\pi f_c R^2 \int_0^{N_{\text{H}}} \frac{\hat{N}_H}{R^2} \frac{\Delta \rho}{\Delta \hat{N}_H} d\hat{N}_H,$$

and the wind efficiency, defined as the ratio of the rate of kinetic energy injected into the ISM and intergalactic medium (IGM)
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Table 6

| OBS    | Instr. | \(M\) (abs1) | \(\epsilon_K\) (abs1) | \(M\) (abs2) | \(\epsilon_K\) (abs2) | \(M\) (tot) | \(\epsilon_K\) (tot) |
|--------|--------|--------------|------------------------|--------------|------------------------|--------------|------------------------|
| OBS1   | XIS FI | 1.0 ± 0.6   | 0.05 ± 0.03            | 2.2 ± 1.5   | 0.63 ± 0.47            | 3.2 ± 1.5   | 0.63 ± 0.47            |
| OBS2   | XIS FI | 0.9 ± 0.6   | 0.06 ± 0.04            | 1.0 ± 0.5   | 0.39 ± 0.37            | 1.5 ± 0.5   | 0.39 ± 0.37            |
| OBS3   | XIS FI | 4.6 ± 0.4   | 0.01 ± 0.01            | 1.8 ± 1.2   | 0.33 ± 0.34            | 2.3 ± 1.2   | 0.33 ± 0.34            |
| OBS1   | XIS BI | 1.7 ± 1.7   | 0.11 ± 0.13            | 4.2 ± 1.1   | 1.1 ± 1.2              | 5.9 ± 1.4   | 1.1 ± 1.2              |
| OBS2   | XIS BI | 2.3 ± 2.2   | 0.24 ± 0.26            | 2.7 ± 1.6   | 1.1 ± 1.3              | 4.8 ± 1.6   | 1.1 ± 1.3              |
| OBS3   | XIS BI | 1.6 ± 1.6   | 0.09 ± 0.14            | 3.4 ± 1.3   | 1.2 ± 1.5              | 5.6 ± 1.3   | 1.2 ± 1.5              |
| Epoch 1| ACIS S3| 0.8 ± 0.8   | 0.02 ± 0.02            | 1.2 ± 0.8   | 0.25 ± 0.11            | 2.1 ± 0.1   | 0.25 ± 0.11            |
| Epoch 2| EPIC pn| ···          | ···                    | ···         | ···                    | ···         | ···                    |
| Epoch 3| EPIC pn| ···          | ···                    | ···         | ···                    | ···         | ···                    |
| Epoch 4| EPIC pn| ···          | ···                    | ···         | ···                    | ···         | ···                    |
| Epoch 5| ACIS S3| 0.9 ± 0.8   | 0.05 ± 0.03            | 2.3 ± 1.5   | 1.4 ± 1.4              | 3.2 ± 1.5   | 1.4 ± 1.4              |

Notes.

1. Estimated values of the outflow properties of APM 08279+5255 based on a model that includes an absorbed power law and a two-component outflow (MODEL3 of Tables 3 and 4) for the Suzaku and Chandra observations and a single-component outflow for the XMM-Newton observations (MODEL1 of Table 4). The values of \(M\) and \(\epsilon_K\) are obtained from Equations (4) and (5) assuming \(M_{\text{BH}} \sim 10^{12} \mu_1^2 M_\odot\) (see Section 2.1) and \(L_{\text{bol}} = 7 \times 10^{39} \mu_1^2 L_\odot\) (Iwasawa et al. 1998; Riechers et al. 2009).

2. We provide two estimates of \(M(\text{tot})\) and \(\epsilon_K(\text{tot})\). The estimate on the left corresponds to the case where the angle between our line of sight and the outflow direction is zero while the one on the right corresponds to an angle of 10°.

Figure 8. Maximum velocity \(v_{\text{max}}\) (upper panel) and total column density of the outflow \((\log(N_{\text{H}}/\text{cm}^{-2}))\); lower panel) vs. photon index (\(\Gamma\)) for our eight deep observations. \(v_{\text{max}}\), \(\log(N_{\text{H}}/\text{cm}^{-2})\), and \(\Gamma\) were derived from fits to the spectra of APM 08279+5255 with a model that included an absorbed power-law and two-component outflow (MODEL2 of Tables 3 and 4) for the Suzaku and Chandra observations and a single-component outflow for the XMM-Newton observations (MODEL1 of Table 4). Errors shown are at the 68% confidence level. In each panel the Suzaku data points are displayed as a single point that represents the weighted (by total counts) mean of the three Suzaku observations. Data shown with circles, a star, and squares are obtained from Chandra, Suzaku, and XMM-Newton observations, respectively.

(A color version of this figure is available in the online journal.)

by the outflow to the quasars bolometric luminosity, is

\[
\epsilon_K = \frac{c^2}{L_{\text{bol}}} \int (\gamma - 1) dM = \frac{4 \pi c^2 f_K M_p R^2}{L_{\text{bol}}} \Delta R \times \int_0^{N_{\text{H}}}(\gamma - 1) v(\dot{N}_{\text{H}}) d\dot{N}_{\text{H}}.
\]

In Equations (4) and (5), \(f_K\) is the global covering factor, \(N_H\) is the column density, \(R\) is the radius, and \(\Delta R\) is the thickness of the absorber. We note that for an absorber with constant non-relativistic speed \((v/c \ll 1)\) Equations (4) and (5) have the same form as the ones used in Saez et al. (2009) and Charters et al. (2009b) (see, e.g., Equation (4) of Saez et al. 2009). The velocity profile assumed in our models is given by Equation (3), therefore Equations (4) and (5) contain the dependence of the estimated outflow properties on the model parameters of the velocity profile. To obtain error bars for \(\epsilon_K\) and \(M\), we performed a Monte Carlo simulation, assuming a uniform distribution of the parameters \(f_K, R\), and \(R/\Delta R\) around the expected values of these parameters, and a normal distribution for \(\log N_H\), \(v_{\text{min}}\), and \(v_{\text{max}}\) (described by the parameters in Tables 3 and 4). Specifically, we assume a global covering factor lying in the range \(f_K = 0.1-0.3\), based on the observed fraction of BAL quasars (e.g., Hewett & Foltz 2003; Gibson et al. 2009) and a fraction \(R/\Delta R\) ranging from 1 to 10 based on current theoretical models of quasar outflows (Proga et al. 2000; Proga & Kallman 2004). Based on our estimated maximum velocities \((v_{\text{max}} \sim 0.7c)\); see, e.g., Charters et al. 2009b) and the fast variability of the outflow, we expect that \(R\) will be close to the Schwarzschild radius \((R_S)\). Therefore in the Monte Carlo simulation we allow \(R\) to vary between \(3R_S\) and \(15R_S\).

In Table 6, we show the mass-outflow rate \(M\) and the efficiency \(\epsilon_K\) of the wind in each observation. The parameters used in Equations (4) and (5) to derive \(M\) and \(\epsilon_K\) were obtained from spectral fits of MODEL2 to the Suzaku and Chandra observations, and through the use of MODEL1 for the XMM-Newton observations (see Tables 3 and 4). For the Suzaku and Chandra observations, we estimate \(M\) and \(\epsilon_K\) for the slow and fast component of the outflow. The total mass-outflow rate and efficiency are obtained by summing the contributions of the slow and fast outflow component (MODEL2, Section 3.3.2).

22 For a constant velocity, i.e., a p-type profile (Equation (3)) with \(p = 0\) and \(v_{\text{min}} = v\), then Equation (4) reduces to \(M = 4 \pi f_K R^2 / \Delta R N_{\text{H}} M_p v\). Also, since \(v \approx 1 + v^2 / (2c^2)\) \((v/c \ll 1)\) Equation (5) becomes \(\epsilon_K = M v^2 / (2L_{\text{bol}})\).
This tendency can be seen more clearly in Figure 9 where we have plotted the total efficiency ($\epsilon_K$) and $\Gamma$ for our eight observations of APM 08279+5255. $\epsilon_K$ and $\Gamma$ were derived from fits to the spectra of APM 08279+5255 with a model that included an absorbed power-law and two-component outflow (MODEL2 of Tables 3 and 4) for the Suzaku and Chandra observations and a single-component outflow for the XMM-Newton observations (MODEL1 of Table 4). Errors shown are at the 68% confidence level. The Suzaku data points are displayed as a single point that represents the weighted (by total counts) mean of the three Suzaku observations. Data shown with circles, a star, and squares are obtained from Chandra, Suzaku, and XMM-Newton observations, respectively.

(A color version of this figure is available in the online journal.)

when multiple components are required to fit the data. In the case of the XMM-Newton observations no summing is required since a one-component wind model (MODEL1, Section 3.3.2) provides better fits (in a statistical sense) to the spectra of APM 08279+5255 (see Section 3.3.2). In Table 6, assuming that the outflow is viewed along our line of sight, we show that during the observations of APM 08279+5255 the total mass-outflow rate varied between $21^{+19}_{-13}$ and $65^{+58}_{-24}$ $M_\odot$ yr$^{-1}$ ($\mu_L = 100$) and the total efficiency varied between $0.2^{+0.2}_{-0.1}$ and $2.3^{+1.1}_{-1.5}$. However, the total values of $\dot{M}$ and $\epsilon_K$ are $\sim$10% and $\sim$50% higher, respectively, if we assume an outflow forming an angle of $10^\circ$ with our line of sight (see Table 6). In Table 6, we also show that an important fraction ($\sim$10%) of the bolometric energy of APM 08279+5255 is injected into the surrounding galaxy through quasar winds.

As Figure 8 shows the softer spectra probably result in a faster and more massive (higher total column density) wind. This tendency can be seen more clearly in Figure 9 where we have plotted the total efficiency ($\epsilon_K$) as a function of the photon index ($\Gamma$). We note that a small contribution to the error bars ($\lesssim$20%) of $\epsilon_K$ arises from errors in the fitted parameters (i.e., $v_{\min}$, $v_{\max}$, and $\log N_H$) while most of the error in $\epsilon_K$ is due to the uncertainty of $R$, $f_i$, and $R/\Delta R$.

The 0.5–8 keV flux of APM 08279+5255 varies by up to 50% in the observations of our study (see Table 1). These flux changes appear to be correlated to changes of the maximum outflow velocity (see Figure 10, left panel). The observed changes in flux may be caused by changes in the luminosity of the ionizing source. By fitting our outflow model to the X-ray spectra of APM 08279+5255, we obtain the intrinsic (unabsorbed) 2–10 keV rest-frame X-ray luminosity of the ionization source ($L_{2–10}$; see Tables 3 and 4). We find that the maximum velocity of the outflow is possibly correlated to the intrinsic luminosity of the ionizing source (see Figure 10, right panel). From the radiative outflow wind equation, we obtain that the terminal velocity of the wind is $v_\infty \propto \sqrt{\Gamma f L}$, where $L$ is the luminosity producing the radiative driving and $\Gamma f$ is the force multiplier (see Section 4 for an analysis describing the dependence of $\Gamma f$ with the photon index). This equation predicts that an increase in the luminosity of the ionizing source should result in an increase of the terminal velocity of the outflow as observed. The Suzaku observations of APM 08279+5255 do not show any significant changes of $\Gamma f$, $v_{\max}$, the total column density, and $L_{2–10}$ (see Table 3). In Figures 8–10, we therefore chose to represent the Suzaku observations with one data point. The Suzaku data point in each figure is the weighted mean of the three Suzaku observations.

As a final comment, the ionization parameter obtained from the spectral fits is based on the assumption that the incident spectrum is a pure power law with a fixed slope ($\alpha = -1$). In reality the spectra are likely more complex and variable than assumed in our model. Our simple approach provides reliable constraints on the column density and velocity of the outflow. However, since the ionization parameter depends on the SED from 1–1000 Ry (see Appendix A.1) we do not expect that fits of our quasar-outflow model to the spectra of APM 08279+5255 to constrain the ionization parameter since our model assumes a fixed SED. What our model does constrain is the temperature of the absorber which is a reliable indicator of the degree of ionization of the outflowing gas.

### 4. Influence of the SED on the Dynamics of the Outflow

In Section 3, we presented a quasar-outflow model that was fit to X-ray observations of APM 08279+5255 in order to constrain the column densities of the absorbers, their ionization state, their terminal velocity, and their ionization parameter. Using this model, we find that the column density of the absorbers is $N_H \approx 10^{24}$ cm$^{-2}$, the ionization parameter is $\xi \approx 10^5$, and the ionization parameter is $\log f \approx 3.8$. These values are consistent with previous studies that have observed similar objects.

For example, for a fixed column density and velocity profile we have checked that approximately the same absorption features are generated if we use an incident power-law SED with $\alpha = -1.0$ and $\log \xi \approx 4.5$, an incident power-law SED with $\alpha = -1.2$ and $\log \xi \approx 3.8$, or an incident Mathews–Ferland SED with $\log \xi = 4.7$. We note that the average temperatures of the gasses producing these absorption profiles are approximately independent of the incident SEDs and lie within the range of $6.6 \lesssim \log T \lesssim 6.8$. However, since the ionization parameter depends on the SED from 1–1000 Ry (see Appendix A.1) we do not expect that fits of our quasar-outflow model to the spectra of APM 08279+5255 to constrain the ionization parameter since our model assumes a fixed SED. What our model does constrain is the temperature of the absorber which is a reliable indicator of the degree of ionization of the outflowing gas.
and their outflow velocities. The outflow models used to fit these X-ray data assumed that the incident SED is a power law with a spectral index of $\alpha = -1$. In this section, we attempt to understand the influence of the incident SED on the dynamics of the outflow. We vary the SED to obtain insight into the dependence of the force multiplier on the incident SED, however, we do not fit any data with variable SEDs. This section extends the analysis presented in Section 3.3 from Chartas et al. (2009b) by providing an analysis of force multipliers as a function of the spectral changes of a Mathews–Ferland SED, while, in the Chartas et al. (2009b) paper we performed the same analysis but using a pure power-law SED. Here we focus on the new results that are based on more realistic SEDs.

4.1. The Dependence of the Force Multiplier on the Photon Index and $\alpha_{ox}$ for a Mathews–Ferland SED.

As suggested in Chartas et al. (2002, 2009a) and Saez et al. (2009), it is plausible that the driving force on the high-energy absorbers is produced initially by X-rays. The short-term variability timescale of the X-ray BALs of AGN 08279+5255 suggests a launching radius of $\lesssim 10R_S$ and recent studies of AGN employing the microlensing technique indicate that the X-ray emission region of the hot corona in AGNs is compact with a half-light radius of a few $R_S$ and their UV regions are roughly a factor of 10 larger (e.g., Morgan et al. 2008; Chartas 2009a). Therefore UV radiation is not expected to contribute initially at small radii to driving the X-ray absorbing outflow. However, as the outflowing absorber gets further away from the source the contribution of the UV photons to the driving force will increase relative to that of the X-ray photons. To investigate the driving mechanism of the wind, we calculated the force multipliers for SEDs that extend to radio wavelengths and estimated the effect of changes in $\Gamma$. In Chartas et al. (2009a), we described the dependence of the force multiplier on the photon index assuming the SED is a power-law extending from the UV (or 1 Ryd $\sim 13.6$ eV) to hard X-rays (or $10^4$ Ryd $\sim 100$ keV). In those calculations we assume SEDs with two different values of the power-law photon index. A “soft” ($\Gamma = 2.1$) and a “hard” ($\Gamma = 1.7$) SED. In this work, we extend our simulations to include a standard and a slightly modified version of the Mathews–Ferland SED (Mathews & Ferland 1987). For each SED we calculated the continuum ($M_C$) and the line ($M_L$) components of the force multiplier. $M_t$ depends on an additional parameter, $t$, which is commonly referred to as the “effective electron optical depth” and encodes the dynamical information of the wind in the radiative acceleration calculation (see Appendix A.5). For our calculations, we have assumed $\log \Gamma = -7$.

The standard Mathews–Ferland SED is characterized by $\alpha_{ox} = -1.41$ and by a power-law spectral index of $\alpha_X = -0.7$ ($\Gamma = 1.7$) which extends from 27 Ry ($\sim 0.36$ keV) to 7.4 $\times$ 10$^3$ Ry ($\sim 100$ keV). The modified Mathews–Ferland SED is similar to the standard one but with $\alpha_X = -1.1$ and $\alpha_{ox} = -1.52$ (see Figure 11 to see the different SEDs used). In the left panel of Figure 12, we show that for low-ionization parameters ($\log \xi \lesssim 2$) the UV dominates the driving of the wind, therefore in this regime there is no major change in the force multipliers when we compare the soft and hard Mathews–Ferland SEDs. However at $\log \xi \gtrsim 2$, the line force multipliers for the soft Mathews–Ferland SED case are larger than those for the hard SED case. This effect is produced because in the case of a Mathews–Ferland SED with a soft X-ray spectrum ($\Gamma = 2.1$) the outflowing gas does not become very ionized at high levels of the ionization parameter compared to the case of a Mathews–Ferland SED with a hard X-ray spectrum ($\Gamma = 1.7$). We conclude that an ionizing source that is relatively soft in the X-ray band will result in a force multiplier that remains relatively large even at ionization levels of the outflowing absorber of $\log \xi \gtrsim 3$. This prediction is consistent with the observed correlation of maximum outflow velocity with the X-ray photon index. We modified the SEDs by including a warm-absorber shield with $\log(N_H/cm^{-2}) = 23$ and $\log \xi_{sh} = 3.1$ (Figure 12, right panel; see also Figure 11 to see the shielded SED). The motivation for the inclusion of this absorbing shield is based on the fact that both observations and theoretical models of radiatively driven winds suggest its existence (e.g., Murray et al. 1995; Proga & Kallman 2004). We

Figure 11. Modified Mathews–Ferland SEDs used to calculate force multipliers in Section 4.1. The $x$-axis is the logarithm of frequency (in Ry units) and the $y$-axis is in units of the logarithm of the flux times the frequency (arbitrary units). The left and right panels correspond to two modified versions of the Mathews–Ferland SED. In the left and right panels $\Gamma = 2.1$ and $\Gamma = 1.7$ with $\alpha_{ox} = -1.52$. The middle panel corresponds to the standard Mathews–Ferland SED, i.e., $\Gamma = 1.7$ with $\alpha_{ox} = -1.41$. In each panel, the dotted line is the unabsorbed SED and the solid line is the shielded SED (with $\log \xi_{sh} \sim 2.9$).

(A color version of this figure is available in the online journal.)
note that the observed absorption at rest-frame energies \( \lesssim 2 \) keV appears to be produced by gas of low-ionization parameter and could therefore be associated with this proposed shield. The main effect of including a shield is a larger increase of the line force multipliers for the soft SED case (\( \Gamma = 2.1 \)) compared to the increase produced by the hard SED case (\( \Gamma = 1.7 \)) for \( \log \xi \gtrsim 2 \). We also find that by including a shield we obtain significant line force multipliers at ionization levels that are larger than the ones possible with no shield present. This effect is especially important in the soft SED case.

In the process of changing the X-ray photon index from the default value of \( \Gamma = 1.7 \) (hard spectrum) to \( \Gamma = 2.1 \) (soft spectrum) in the Mathews–Ferland SED, we also changed \( \alpha_{ox} \) from \(-1.41 \) to \(-1.52 \). To test the sensitivity of the force multiplier to changes of the \( \alpha_{ox} \) of the SED, we estimated the force multiplier for the case where \( \alpha_{ox} \) changed while the X-ray spectral slope remained constant. In order to produce this effect, we increased the blue bump of the Mathews–Ferland SED by changing the default value of \( \alpha_{ox} \). This difference in sensitivity is associated with the fact that the UV covers the range where most of the absorption lines lie. We also modified the SEDs by including an absorbing shield with \( \log(N_{H}/\text{cm}^{-2}) = 23 \) and \( \log \xi_{sh} = 3.1 \) (see Figure 11). In the right panel of Figure 13, we show that the effect of adding this warm-absorber shield is an increase of the force multiplier for soft SEDs even at high ionization levels.

We note that we used a moderate amount of shielding for the estimates shown in the left panels of Figures 12 and 13. The combination of moderate attenuation and high force multipliers in this type of shield is expected to produce high velocity outflows (Chelouche & Netzer 2003). If we use an absorbing shield with a relatively low ionization level, we find that the large absorption from the shield will attenuate a large fraction of the UV and X-ray photons, and therefore prevent the outflow from reaching high terminal velocities.

In general, the presence of an absorbing shield will increase the differences between the line force multipliers for the soft and hard SED cases. These differences will be important for shields with ionization parameters in the range of \( 1.0 \lesssim \log \xi_{sh} \lesssim 1.8 \) for the power-law SED case and will be important for shields with ionization parameters in the range of \( 1.2 \lesssim \log \xi_{sh} \lesssim 3.1 \) for the Mathews–Ferland SED case (see Appendix A.6). For values of the ionization parameter of the shield over these boundaries, the shield will be transparent to incident radiation and the force multipliers will be similar to ones with no shield present (left panels of Figures 12 and 13). For values of \( \log \xi_{sh} \lesssim 1.0 \) the large absorption produced by the shield will result in a weak outflow (see Chelouche & Netzer 2003).
If the $\Gamma - v_{\text{max}}$ trend is confirmed with additional observations, we plan to produce a more sophisticated model that will include more realistic kinematic, ionization, and absorption properties of the outflow. If the $\Gamma - v_{\text{max}}$ relation is real we would also like to know if the changes in $\Gamma$ are accompanied by changes of $\alpha_{\text{ox}}$. Studies of correlations between outflow properties and the SED of the ionizing source will provide crucial information regarding the driving mechanism of the outflow. Simultaneous multi-wavelength observations of sources such as APM 08279+5255 that show fast outflows will therefore be essential for the study of quasar outflows. We note that for the SEDs analyzed in this section the contribution to the force multiplier from highly ionized iron lines such as Fe xxv Kα (1s$^2$ - 1s2p; 6.70 keV) and/or Fe xxvi (1s - 2p; 6.97 keV) is relatively small. However, we observe significant blueshifts of the X-ray BALs of APM 08279+5255 indicating highly ionized material moving at near-relativistic velocities. One possible interpretation is that we are observing absorption from outflowing highly ionized material that was accelerated at a previous time when it was at a lower ionization level. We note that a better understanding of quasar outflows will have to await the development of more sophisticated numerical codes that combine MHD simulations of the outflowing material and the photoionization properties of the wind. Such an analysis is beyond the scope of this paper.

5. CONCLUSIONS

We have re-analyzed eight long exposure X-ray observations of APM 08279+5255 (two Chandra, three XMM-Newton, and three Suzaku) using a new quasar-outflow model. This model is based on CLOUDY simulations of a near-relativistic quasar outflow that were used to generate XSPEC table models.

The main conclusions from this re-analysis are the following. (1) In each observation, we have found X-ray BALs that have been detected at a high level of significance. Specifically, we find strong and broad absorption at rest-frame energies of 1–4 keV (low energy) and 7–18 keV (high energy). (2) We confirm that the medium producing the low-energy absorption is a nearly neutral absorber with a column density of log($N_{\text{H}}$/cm$^{-2}$) $\approx$ 23. The medium producing the high-energy absorption appears to be outflowing from the central source at relativistic velocities (between 0 and 0.7c) and with a range of ionization parameters (3 $\leq$ log $\xi$ $\leq$ 4). The maximum detected projected outflow velocity of $\sim$0.7c constrains the angle between our line of sight and the wind direction to be $\lesssim 22^\circ$. The short timescale variability ($\lesssim$ week in the rest frame) of the high-energy absorption implies that X-ray absorbers are launched from distances of $\sim 10 R_S$ from the central source (where $R_S$ is the Schwarzschild radius). (3) We also confirm trends between the maximum projected outflow velocity ($v_{\text{max}}$) with the photon index ($\Gamma$) and the intrinsic (unabsorbed) X-ray luminosity at the 2–10 rest-frame band; i.e., softer and more luminous X-ray spectra generate larger outflow terminal velocities. We also find that the total column density ($N_{\text{H}}$) of the outflow increases with $\Gamma$. The trends found suggest that the wind becomes more powerful as the incident spectrum becomes softer. This tendency is confirmed through estimates of the efficiency of the wind. Additionally, we estimate that a significant fraction (>10%) of the total bolometric energy over the quasar’s lifetime is injected into the intergalactic medium of APM 08279+5255 in the form of kinetic energy.

In this work, we modeled the spectrum of the central ionizing source with a power-law SED and with Mathews–Ferland SEDs and found that variations of the X-ray and UV parts of the SEDs will produce important changes in the strength of the radiative driving force. These results support the observed trend found between the outflow velocity and X-ray photon index in APM 08279+5255. In general, we find as expected that the presence of a moderate absorbing shield results in more powerful outflows (Chelouche & Netzer 2003). Specifically, we find that shields with column densities of log($N_{\text{H}}$/cm$^{-2}$) $\sim$ 23, covering an optically thin outflow, provide a significant increase in the driving force when their ionization parameters are in the range of 1.0 $\leq$ log $\xi_{\text{ox}}$ $\leq$ 1.8 for the case of a power-law SED and in the range of 1.2 $\leq$ log $\xi_{\text{ox}}$ $\leq$ 3.1 for the case of a Mathews–Ferland SED. Therefore the strength of the radiative driving force depends critically on both the column density of the shield and its ionization level. A confirmation of the results found in our simulations of quasar outflow will require new deeper X-ray multi-wavelength observations of quasars that contain clear signs of fast outflow. Such observations will allow us to correlate the properties of the outflow with properties of the SED and thus test our predictions.

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APPENDIX

A.1. Ionization Parameter

There are two definitions of the ionization parameter that are broadly used in the scientific literature. The first definition, which will be mostly adopted in this work, is the ionization parameter of Tarter et al. (1969) given by

$$\xi = \frac{L_\text{I}}{n_\text{H} \pi R^2} = \frac{4\pi}{n_\text{H}} \int_{1R_\text{S}}^{1000R_\text{S}} F_\nu d\nu = \frac{4\pi F_\nu}{n_\text{H}},$$

where $L_\text{I}$ is the ionizing luminosity, $F_\nu$ is the ionizing flux, $F_\nu$ is the incident flux, $n_\text{H}$ is the hydrogen density, and $r$ is the source–cloud separation. A second definition of the ionization (Davidson 1977) parameter is given by the ratio of photons that can ionize hydrogen to the number of hydrogen atoms in a spherical layer at a distance $r$ from an illuminating point source, i.e.,

$$U = \frac{Q}{4\pi r^2 c n_\text{H}}, \text{ where } Q = \int_{1R_\text{S}}^{\infty} \frac{L_\nu}{h^\nu} d\nu. \quad (A2)$$

We note that for a pure power law (i.e., $F_\nu \propto \nu^\alpha$), the analytic expressions to convert between $\xi$ and $U$ (valid for $\alpha < 0$) are

$$\log \xi = \begin{cases} \log U + 1.754 & \alpha = -1 \\ \log U + 0.914 + \log \left(-(1000^{\alpha+1} - 1) \frac{\alpha}{\alpha - 1}\right) & \alpha \neq -1. \end{cases} \quad (A3)$$

A.2. When Can an Absorption Slab be Considered Thin?

The fraction of flux absorbed in the rest-frame of a layer of gas depends on the ionization state of the absorber, its column density, and the SED of the illuminating source. Our quasar outflow code calculates the absorption profiles resulting from absorption of the central source spectrum by ionized
gas in an accelerated outflow. One of the assumptions of our quasar-outflow model is that the absorption layer producing the observed X-ray BALs has a plane-parallel geometry with a thickness that is much smaller than the distance from the central source.

We therefore expect any decrease in the ionization parameter across an absorbing layer to be predominantly due to the absorption of the flux in the layer rather than to the $1/R^2$ decrease of the ionization parameter.

We will refer to a layer as optically thin if the change between the ionization parameter on the illuminated side and the dark side of the layer is less than 0.05 dex.

In Figure A.1, we show the column density of a thin layer that will produce a decrease of 0.05 dex of the ionization parameter across this layer as a function of the ionization parameter at the front surface of the layer. We plot this relation for power-law SEDs with a photon index of $\Gamma = 1.5$ and $\Gamma = 2.2$, respectively. Both spectra are defined between 1 Ryd and $10^8$ Ry.

**Figure A.1.** Limiting column density at which a layer will be considered thin. In this case we arbitrarily define a layer as thin when the ionization parameter decreases after crossing the layer less than 0.05 dex due to absorption. The solid and dotted lines represent a soft spectrum power-law ($\Gamma = 2.2$) and hard power-law spectrum ($\Gamma = 1.5$), respectively. Both spectra are defined between 1 Ryd and $10^8$ Ry.

A.3. Near-relativistic Quasar Outflow Code: Assuming an Outflow with a Constant $\Delta v$ between Layers

Since our library of cloudy simulations was generated for a specific turbulent velocity, we adjust the relative speed between layers $i$ and $i+1$ to be constant (i.e., $\Delta v_i = (v_{i+1} - v_i)/(1 - v_i v_{i+1}/c^2)$ constant). Assuming $N_l$ layers, we initialize the parameters defining our profile by the following:

1. Deriving the velocity profile, which satisfies $v_0 = v_{\text{min}}$; $v_N = v_{\text{max}}$ ($\Delta v' = \Delta v$).
2. Deriving $N_{\text{HI}}$ through the use of $N_{\text{HI}} N_{\text{H}} = N_H / k$; this result comes from $\nu(N_{\text{HI}}) = \nu_{\text{min}} + k N_{\text{H}}^d / (k = (\nu_{\text{max}} - \nu_{\text{min}}) / N_{\text{H}}$, where $N_{\text{H}}$ is the total column density of the outflow). Using the last expression, we calculate $N_{\text{HI}}$ from $N_{\text{HI}}$ starting from $N_{\text{H}} = 0$. (3) Calculating the average velocity $v_{\text{av}} = (v(r_i) + v(r_f))/2$, the column density $\Delta N_{\text{HI}} = N_{\text{HI}} - N_{\text{HI}}$?, the density $n_i = n(v_{\text{av}})$, and the radial steps $\Delta r = \Delta N_{\text{HI}}/n_i$ of each layer.

We note that our assumptions are valid as long as $\Delta v < 0.05$.

In each layer, we subtract the absorption and add the emission. Since $\text{xstar}$ does not include a “Compton-scattered” component for the emission, we add this component in a similar way as the one described in Schurch & Done (2007). The Compton-scattered emission component is obtained by calculating the Thomson-scattered flux of each layer, where the incident spectrum is the output from the previous layer. Since in the case of Schurch & Done (2007) the calculations were made assuming spherical symmetry of the multilayer absorber, with global covering factors equal to one, we use similar assumptions to obtain the emission of each layer. We calculated the emission from a spherical shell by adding the spectral contribution from each solid angle of the layer. The emission from each solid angle of the shell is corrected for Doppler beaming of material outflowing at a projected velocity with respect to a fixed line of sight.

The spectra of the incident, absorbed and emitted continua for each of the initial values of the ionization parameters used in these calculations of absorption line profiles are presented in the six panels of Figure A.2. We find a remarkable similarity of Figure A.2 with Figure 7 of Schurch & Done (2007). The small differences found in our results when compared to those of Schurch & Done (2007) are mainly associated with differences in the details of the calculations. Specifically, Schurch & Done (2007) pass the output flux from one layer to the other internally, while in our approach we perform separate

25 Let us assume a relatively faint AGN with $L_x \sim 10^{42}$ erg s$^{-1}$ with an absorbing layer of $\log(nH/cm^2) = 22$, $nH = 10^8$ cm$^{-3}$, and an ionization parameter of $\log(\xi) = 3$ on the illuminated side of the layer. Since $\xi = L_x/(nR^2)$, $R \sim 3 \times 10^{15} n_{H}^{-1/2} \text{cm}$; therefore $\Delta R/R \sim 0.3 n_H^{-3/2}$. Since this is an extreme case (faint AGN and highly ionized layer), in general we expect $\Delta R/R \ll 0.1$.

26 If we define $\xi_f$ and $\xi_i$ as the ionization parameters at the illuminated front and back sides of the layer, respectively, then our definition of a thin layer can be written as $\log(\xi_f / \xi_i) < -0.05$. In addition, if we assume that the incident flux on the layer is $F_{\nu i}$, we have that $\log(\xi_f / \xi_i) = \log(\xi_f / \xi_i) F_{\nu i} e^{-\tau_i} / \nu_{\text{max}} F_{\nu d} \sim \log(1 - (\tau_i)) \sim \tau_i/\nu_0$, where $\nu_0 \approx 1000 \text{Ryd}$ and $\nu_i$ is the average opacity through the layer between $v_F$ and $v_i$. Therefore, our definition of a thin layer is equivalent to a layer with an average opacity of $(\tau_i) \lesssim 0.1$.

27 The Thomson-scattered flux is the incident flux multiplied by $1 - e^{-\Delta N_{\text{HI}} \sigma_T}$, where $\Delta N_{\text{HI}}$ is the column density of the layer and $\sigma_T$ is the Thomson cross section.

28 In Schurch & Done (2007), the authors use the same photon field $\text{xstar}$ propagates internally, therefore their approach is consistent with a single,
photoionization runs from one layer to the next. Possibly an important factor that contributes to the discrepancies between the two codes is that in our calculations we approximate the incident flux on each layer as being the unabsoresourced source SED. On the other hand, Schurch & Done (2007) use the absorbed SED to perform the photoionization calculations in each layer. We expect our approximation of using the unabsoresourced source SED as incident on all layers to break down at low ionization levels where absorption through a layer may significantly change the SED. This explains why our results begin to noticeably differ from those of Schurch & Done (2007) at log ξ ≲ 3.

In Figure A.3, we plot the absorbed and emitted spectra in the energy range where we detect iron absorption (∼7–9 keV) for three different values of the exponent of the p-type velocity profile (see Equation (3), Section 3) of p = 5.0, 1.0, and 0.2. For these comparison tests, we set v_{min} = 0, v_{max} = 0.3c, N_{H} = 3 \times 10^{23} \text{ cm}^{-2}, n_{0} = 10^{12} \text{ cm}^{-3}, and log ξ = 3. We find agreement between our code and that of Schurch & Done (2007) as shown in the comparison between the absorption and emission profiles presented in Figure A.3 and Figure 4 of Schurch & Done (2007). Our emission spectra for the case of a velocity profile with an exponent of p = 5 differ from those derived by Schurch & Done (2007) (see Figure 4 of Schurch & Done 2007) mainly because in their simulations the turbulent velocity is set to be variable in order to model fine structures in the spectra. In our simulations, we fix the turbulent velocity in the outflow, and therefore we are not able to reproduce fine details (≲1500 km s^{-1}) in the spectra. This is not a significant problem since we are mainly interested in simulating the BALs detected in the X-ray spectra of BAL quasars.\(^{29}\)

We conclude that our quasar outflow code provides results that are very similar to those found in the independent code of Schurch & Done (2007) as long as the SED does not change significantly across the multilayer. For our study we have mostly selected quasar outflows of highly ionized material (i.e., log ξ ≥ 3.0) and therefore expect the SED of the central source not to be significantly attenuated across the outflowing multilayer. As a final remark, we note that in our quasar outflow code the photoionization calculations at each layer use a library of preexisting runs that can be performed either with CLOUDY XSTAR or any other photoionization code. This presents an advantage over the quasar outflow code XSCORT in the sense that we can compare photoionization calculations performed with different photoionization codes which might incorporate slightly different atomic physics. Additionally, the

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\(^{29}\) A typical energy resolution of an X-ray telescope (at energies between 1 and 10 keV) is ∼100 keV, therefore for an Fe xxv Kα (1\(\alpha^2 - 1\alpha \mu\); 6.70 keV) line we will not be able to resolve features with Doppler broadenings ≲ 4000 km s^{-1}. 

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**Figure A.2.** 0.3–13 keV spectra of the incident (full line), transmitted (dashed-line), and emitted (dotted-line) continua for different ionization levels of the outflowing material simulated with our quasar outflow code. In panels 1–3 (top, left to right), the ionization levels of the outflowing material are log ξ = 2.75, 3.0, and 3.25, respectively. In panels 4–6 (bottom, left to right), the ionization levels of the outflowing material are log ξ = 2.75, 3.0, and 3.25, respectively. For all these simulations, the total number of layers is N_{lay} = 100, the total column density of the outflowing material is N_{H} = 3 \times 10^{23} \text{ cm}^{-2}, the initial gas density is 10^{12} \text{ cm}^{-3}, and the velocity of the outflow is assumed to vary linearly between 0 and 0.3c. These results are in good agreement with those of Schurch & Done (2007) as evident from a comparison between this figure and their Figure 7. (A color version of this figure is available in the online journal.)

**Figure A.3.** Emitted (upper panel) and absorbed (lower panel) spectra in the energy range where we detect iron absorption (∼7–9 keV) for three different values of the exponent of the p-type velocity profile (see Equation (3), Section 3) of p = 5.0, 1.0, and 0.2. For these comparison tests, we set v_{min} = 0, v_{max} = 0.3c, N_{H} = 3 \times 10^{23} \text{ cm}^{-2}, n_{0} = 10^{12} \text{ cm}^{-3}, and log ξ = 3. We find agreement between our code and that of Schurch & Done (2007) as shown in the comparison between the absorption and emission profiles presented in Figure A.3 and Figure 4 of Schurch & Done (2007). (A color version of this figure is available in the online journal.)
major advantage of using our outflow code over xscort is a significant shortening in the computing time required for the simulation of an absorption profile.

A.5. Force Multiplier Calculations

In this appendix, we derive a formula for the force multiplier and compare our expression to ones reported in earlier studies (see, e.g., Arav et al. 1994; Mihalas & Mihalas 1984).

A.5.1. Force Multiplier Calculation

For a medium that absorbs radiation, the force per unit volume on the medium is

$$ f_v = \frac{1}{c} \int \alpha_v F_v \, dv, $$  \hspace{1cm} (A4)

where $\alpha_v$ (cm$^{-1}$) is the absorption coefficient and $F_v$ is the incident flux on the medium. Assuming that the flux originates from a point source with luminosity $L_v$ at $r = 0$ the acceleration is given by

$$ \frac{dv(r)}{dt} = \frac{1}{4\pi r^2 \rho(r)c} \int \alpha_v L_v e^{-\tau_v} \, dv. $$ \hspace{1cm} (A5)

The factor $e^{-\tau_v}$ corresponds to the attenuation factor at radius $r$ ($\tau_v(r) = \int_0^r \alpha_v(r') \, dr'$). Assuming that the central source has a mass of $M$, the force equation can be rewritten as

$$ \frac{dv(r)}{dt} = \frac{n_e(r) \sigma_T L_{bol}}{4\pi r^2 \rho(r)c} \frac{M(r) - G M}{r^2} \quad \text{with} \quad M(r) = \int_0^r \alpha_v(r) L_v e^{-\tau_v} \, dv, $$ \hspace{1cm} (A6)

where $L_{bol}$ is the bolometric luminosity, $\sigma_T$ is the Thomson cross section, and $M(r)$ is the force multiplier. $M(r)$ can be interpreted as the ratio of energy absorbed by the medium to the energy absorbed by the electrons.

As a simple example we assume that the medium is a spherical shell with inner and outer radii of $R$ and $R + \Delta R$, respectively. For this case $M(r) = \int M(r) \, dr / \Delta R$; and therefore, the wind equation (A6) is approximated as

$$ \frac{dv(r)}{dt} = \frac{\sigma_T L_{bol}}{1.2 m_p 4\pi r^2 c} \langle M(r) \rangle - \frac{G M}{r^2}. $$ \hspace{1cm} (A7)

In this last stage, we have assumed a high-ionization state for the gas at solar metallicities and therefore $\rho_i / n_e(r) \sim 1.2 m_p$, where $m_p$ is the mass of the proton. Assuming that $v(R_{\text{min}}) = 0$ the solution of Equation (A7) is

$$ v(r) = \sqrt{\frac{2 G M}{r_{\text{Edd}}} \left( \frac{L_{bol}}{1.2 L_{Edd}} \langle M \rangle - 1 \right) \left( \frac{1}{r_{\text{min}}} - \frac{1}{r} \right) }, $$ \hspace{1cm} (A8)

where $L_{Edd}$ is the Eddington luminosity (i.e., $L_{Edd} = 4\pi e G M \mu m_p M/c^2$).

To calculate the force multiplier of a line, we start from Equation (A6). Let us assume that the absorption line has a constant opacity, frequency $\nu_l$, and a width $\Delta \nu_l = \nu_l v_{th}/c$ (where $v_{th}$ is the thermal speed of the absorbing atoms$^{30}$). The characteristic distances of radiative interactions are of the order of $l \sim v_{th}/(\nabla \nu)$. Hence for radially streaming radiation in an expanding medium the optical thickness is

$$ \tau_l = \alpha_l v_{th}/(dv/dr), $$ \hspace{1cm} (A9)

where $\alpha_l$ is the absorption coefficient of the line. We define $\eta_l = \frac{\alpha_l}{n_e \sigma_T}$ and introduce an equivalent electron optical depth scale

$$ t = \tau_l / \eta_l = n_e \sigma_T v_{th}/(dv/dr). $$ \hspace{1cm} (A10)

Therefore, the mean force multiplier is $\langle M(r) \rangle = \int M(r) \, dr / l$, i.e.,

$$ \langle M(r) \rangle = \frac{\int_0^r \alpha_v(t) L_v \, dt}{\int_0^r \eta_l(t) \, dt}. $$ \hspace{1cm} (A11)

Summing up over all absorption lines, we obtain

$$ M(t) = \frac{1}{L_{bol}} \sum_i L_{\nu_l} \Delta \nu_{th,l} (1 - e^{-\eta_l(t)}) \frac{1}{t}. $$ \hspace{1cm} (A12)

To obtain $\alpha_l$ we use Equation (1.78) from Rybicki & Lightman (1985), i.e.,

$$ \alpha_l = \frac{h\nu_l}{4\pi} \eta_l B_{\nu_l} \left( 1 - \frac{g_l}{g_u} \eta_u / \eta_l \right) \phi(\nu). $$ \hspace{1cm} (A13)

Assuming that the absorption line has a square-topped profile of width $\Delta \nu_{th,l} = \nu_l v_{th}/c$, and using $B_{\nu_l} = 4\pi e^4 c^3 / \hbar^2 \nu_l^3 f_l$, where $f_l$ is the oscillator strength we obtain

$$ \alpha_l = \frac{\pi e^2}{m_e c} g_u f_l \left( \frac{g_l}{g_u} - \frac{n_u}{n_l} \right) / \Delta \nu_{th,l}. $$ \hspace{1cm} (A14)

Inserting Equation (A14) into (A12), we reproduce the result of Arav et al. (1994), i.e.,

$$ M(t) = \frac{1}{L_{bol}} \sum_i L_{\nu_l} \Delta \nu_{th,l} \left( 1 - e^{-\eta_l(t)} \right) \frac{1}{t}. $$ \hspace{1cm} (A15)

A.5.2. Comparison with Other Results

The force multiplier mainly depends on the SED of the source, the composition of the gas, and its ionization parameter. In general, a soft spectrum irradiating a gas that is nearly neutral (i.e., low-ionization parameter) will strongly accelerate the gas and the force multiplier will be relatively large.

When the gas is highly ionized it absorbs less radiation and is subject to a weaker radiative driving force (i.e., the force multiplier is relatively small).

Figure A.4 shows the estimated force multiplier assuming a Mathews–Ferland SED. Figure A.4 has four panels, the upper-left panel represents the continuum component of the force multiplier, mainly produced by bound–bound transitions. The other three panels in Figure A.4 show the contribution to the force multiplier from bound–free transitions for three different values of the dimensionless factor $t$; $log t = -6, -7, \text{and} -8$. The line force multipliers increase as $t$ decreases. This increase is noticeable when the medium is not highly ionized ($log U \lesssim -1$; $log \xi \lesssim 0.3$). Our calculations are in good agreement with those performed by Arav et al. (1994) and Everett (2005).
A warm-absorber shielding the outflow may increase the effectiveness of radiation driving. In this appendix, we use the same unabsorbed SEDs used in Section 4 to estimate the amount of shielding required to significantly increase the radiative driving force. Additionally, we estimate the differences between the radiative forces produced by a soft incident spectrum and a hard incident spectrum for different ionization levels of the absorbing outflow. As in Section 4, we assume that the warm-absorber shielding the outflow has $\log(\xi_{sh}) = -2.1$ absorbed Mathews–Ferland SEDs. In the upper-left, upper-right, lower-left, and lower-right panels, we assume shields that attenuate the SEDs with log$(N_{HI}/cm^{-2}) = 23$ and log $\xi_{sh} = 0.6, 1.0, 1.3, 1.6, 1.8,$ and 2.1, respectively. In Figure A.5, we show that $M_L$ is significantly larger for incident SEDs with soft spectra (i.e., $\Gamma = 2.1$) than for incident SEDs with hard spectra (i.e., $\Gamma = 1.7$) especially at low ionization levels of the shielding gas. For values of log $\xi_{sh} \lesssim 0.6$, we do not expect strong radiative driving given the heavy attenuation of the continuum (see, e.g., Chelouche & Netzer 2003). We also note that the force multipliers $M_C$ and $M_L$ are significantly reduced for low ionization levels of the shield as shown in Figure A.5. Additionally, when log $\xi_{sh} \gtrsim 2.0$ the shielding becomes transparent to the radiation and therefore the force multipliers are similar to the ones in the unabsorbed case. Finally from Figure A.5, we see that when the ionization parameter of the shield lies in the range of $1.0 \lesssim \log \xi_{sh} \lesssim 1.8$ the line force multiplier of the outflowing material is greater with the presence of an absorbing shield than without one.

In Figure A.6, we have plotted $M_C$ and $M_L$ as a function of the ionization parameter for soft ($\Gamma = 2.1; \alpha_{ox} = -1.51$) and hard ($\Gamma = 1.7; \alpha_{ox} = -1.41$) absorbed Mathews–Ferland SEDs. In the upper-left, upper-right, lower-left, and lower-right panels, we assume shields that attenuate the SEDs with log$(N_{HI}/cm^{-2}) = 23$ and log $\xi_{sh} = 1.0, 1.2, 1.9, 2.7, 3.1,$ and 3.8, respectively. In the case of a Mathews–Ferland SED incident on a shield with an ionization parameter in the range of $1.2 \lesssim \log \xi_{sh} \lesssim 3.8$, we find that the line force multiplier $M_L$ for soft SEDs (i.e., $\Gamma = 2.1$) extends to larger values of the ionization parameter of the outflowing material compared to hard SEDs (i.e., $\Gamma = 1.7$).

In Figure A.7, we have plotted $M_C$ and $M_L$ as a function of the ionization parameter of the outflow for soft ($\Gamma = 1.7; \alpha_{ox} = -1.51$) and hard ($\Gamma = 1.7; \alpha_{ox} = -1.41$) absorbed...
modified Mathews–Ferland SEDs. In the upper-left, upper-right, lower-left, and lower-right panels, we assume shields that attenuate the SEDs with $\log(N_H/\text{cm}^{-2}) = 23$ and $\log \xi_{\text{sh}} = 1.0, 1.2, 1.9, 2.7, 3.1, \text{and} 3.8$, respectively. In the case of a modified Mathews–Ferland SED incident on a shield with an ionization parameter in the range of $1.0 \lesssim \log \xi \lesssim 5$, we find that the line force multiplier $M_L$ is significantly larger for soft SEDs (i.e., $\alpha_{\text{ox}} = -1.52$) than for hard SEDs (i.e., $\alpha_{\text{ox}} = -1.41$). We note that the line force multiplier for the case of a soft Mathews–Ferland SED incident on a shield with an ionization parameter of $\log \xi_{\text{sh}} = 1.9$ has a value larger than $\sim 1000$ for ionization parameters of the outflowing absorber in the range of $0 \lesssim \log \xi \lesssim 5$. For a shield with $\log \xi_{\text{sh}} \lesssim 1$, we predict that the continuum becomes too attenuated to allow effective radiative driving. When $\log \xi_{\text{sh}} \gtrsim 3.1$, the shield becomes transparent to the incident radiation and therefore the force multipliers are similar to the ones estimated for the unabsorbed case (see the lower-right panels of Figures A.6 and A.7).

In Figure A.8, we plot the temperature of an absorbing shield as a function of its ionization parameter (on its illuminated side)
for a shield with \( \log(N_H/\text{cm}^{-2}) = 23 \). From the analysis in the last three paragraphs and from Figure A.8, we conclude that the most powerful winds are probably produced at temperatures in the range \( 4.5 \lesssim \log(T) \lesssim 5.2 \). This occurs for power-law SEDs incident on shields with \( 1.0 \lesssim \log(\xi_{sh}) \lesssim 1.8 \) and for Mathews–Ferland SEDs incident on shields with \( 1.2 \lesssim \log(\xi_{sh}) \lesssim 3.1 \).

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