The Role of Complex Ionized Absorbers in the Soft X-Ray Spectra of Intermediate Polars

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Abstract

In magnetic cataclysmic variables (mCVs), X-ray radiation originates from a shock-heated, multi-temperature plasma in the post-shock region near the white dwarf’s surface. These X-rays are modified by a complex distribution of absorbers in the pre-shock region. The presence of photoionized lines and warm absorber features in the soft X-ray spectra of these mCVs suggests that these absorbers are ionized. We developed the ionized complex absorber model zxipab, which is represented by a power-law distribution of ionized absorbers in the pre-shock flow. Using the ionized absorber model zxipab along with a cooling flow model with a reflection component, we model the broadband Chandra/High-Energy Transmission Grating (HETG) and Nuclear Spectroscopic Telescope Array (NuSTAR) spectra of two intermediate polars (IPs): NY Lup and V1223 Sgr. We find that this model describes well many of the H- and He-like emission lines from medium-Z elements, which arise from a collisionally excited plasma. However, the model fails to account for some of the He-like triplets from the medium-Z elements, which points toward their photoionized origin. We do not find compelling evidence for a blackbody component to model the soft excess seen in the residuals of the Chandra/HETG spectra, which could be due to uncertainties in the estimation of the interstellar absorption of these sources using the Chandra/HETG data and/or excess fluxes seen in some photoionized emission lines which are not accounted for by the cooling flow model. We describe the implications of this model with respect to the geometry of the pre-shock region for these two IPs.

Unified Astronomy Thesaurus concepts: Cataclysmic variable stars (203); White dwarf stars (1799); Astronomy data analysis (1858)

1. Introduction

Cataclysmic variables (CVs) are interacting binaries consisting of a white dwarf accreting matter from a low-mass companion (usually a late-type main-sequence star; see the review by Mukai 2017). The accretion flow around the white dwarfs is primarily governed by their magnetic fields. For non-magnetic CVs, the accretion disks extend up to the surface of the primary, whereas for polars the magnetic field is strong enough to prevent the formation of an accretion disk. Intermediate polars (IPs) are a subclass of magnetic CVs (mCVs), where a partial accretion disk exists and accretion onto the white dwarf is magnetically funneled onto its poles from the inner edge of the truncated accretion disk.

The X-ray emission from these IPs arises from an accreted-matter shock heated up to high temperatures ($kT \sim 10$–$50$ keV), which must cool before settling onto the surface of the white dwarf. The emergent X-ray spectrum is expected to be the resultant emission from plasma over a continuous temperature distribution, from the shock temperature to the white dwarf’s photospheric temperature. High-resolution X-ray spectra of CVs are found to be similar to the cooling flow spectra seen for clusters of galaxies (Fabian & Nulsen 1977; Fabian 1994). However, the low-temperature emission predicted by classical cooling flow models is absent in clusters of galaxies (see, e.g., Peterson et al. 2003) due to the presence of heating processes, presumably active-galactic-nucleus feedback. On the other hand in CVs, cooling continues until the plasma reaches the white dwarf’s photospheric temperature ($T \sim 10^5$ K). The emergent X-rays from this shock-heated, multi-temperature plasma is modified by the presence of a complex distribution of absorbers in the pre-shock region. This complex absorber is expected to be ionized due to irradiation of the pre-shock flow around the white dwarf. For some IPs, a soft component is seen in the X-ray spectra which (in low- to medium-resolution data) is modeled by a blackbody with a temperature $kT \geq 60$ eV (Evans & Hellier 2007; Anzolin et al. 2008). This soft component is thought to arise from reprocessing of the hard X-rays, although there is considerable uncertainty in the presence of this component.

The X-ray spectra of IPs are often strongly absorbed at a level significantly above the intervening interstellar column. Both the energy dependence of spin-modulation amplitudes and the spectral shape of spin-phase-averaged spectra indicate that a simple absorber is not sufficient (Norton & Watson 1989); these authors used the partial covering absorber model pcfabs available in XSPEC. In pcfabs, some fraction of the emission is assumed to be observed directly, while the rest (“covering fraction”) is seen through a neutral absorber of column density $N_H$. However, Done & Magdziarz (1998) pointed out that the partial covering absorber model is far too simplistic for mCVs. This is because the post-shock region, the source of the X-ray emission, is directly adjacent to the pre-shock flow, the site of the complex absorption. This results in an absorber having a continuous range of $N_H$, each value with its own differential covering fraction (see Figure 8 of Mukai 2017). Done & Magdziarz (1998) proposed to model this using a model in which the differential covering fraction is a power-law function of $N_H$, and encoded this in an XSPEC model pwab.

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¹ More recently, the convolution model partcov can be used to turn any absorber model into a partial covering absorber model.
Table 1
Summary of X-Ray Observations

| Source     | Telescope          | ObsID       | Start Time          | Exposure (ks) |
|------------|--------------------|-------------|---------------------|--------------|
| NY Lup     | Chandra/ACIS-S HETG| 17874       | 2016-05-23 15:24:24 | 49.41        |
|            | Chandra/ACIS-S HETG| 18857       | 2016-05-24 22:04:15 | 32.35        |
|            | Chandra/ACIS-S HETG| 18858       | 2016-05-25 22:32:09 | 23.15        |
|            | Chandra/ACIS-S HETG| 18859       | 2016-05-28 13:14:07 | 26.71        |
|            | NuSTAR             | 3000146002  | 2014-08-09 14:51:07 | 23.00        |
| V1223 Sgr  | Chandra/ACIS-S HETG| 649         | 2000-04-30 16:19:51 | 51.5         |
|            | NuSTAR             | 3000144002  | 2014-09-16 02:26:07 | 20.4         |

In this paper, we propose a further modification of the $pwab$ model, because the accretion flow just above the shock is likely ionized. A photoionization model is usually calculated in terms of a cloud of density $n$ at a distance $r$ from the ionizing source with a luminosity of $L$ as $\dot{L} = L/nr^2$. This can be generalized as the ratio of ionizing flux to density, modulo a geometrical factor $4\pi$, when considering an extended cloud neighboring an extended source of ionizing flux. For the pre-shock accretion flow in mCVs, $\dot{L}$ probably exceeds 10 just above the shock but rapidly decreases away from the shock front, due to geometrical dilution of the ionizing radiation (see Discussion). Observationally, the 0.73 keV edge due to $O_{VII}$ has been detected for V1223 Sgr (Mukai 2017) and V2731 Oph (de Martino et al. 2008). It is likely that the pre-shock flow is the site for both the ionized absorbers and the photoionized emission features originally recognized by Mukai et al. (2003) and confirmed here in this work for NY Lup and V1223 Sgr.

The outline of the paper is as follows: In Section 2 we describe the Chandra/High-Energy Transmission Grating (HETG) and Nuclear Spectroscopic Telescope Array (NuSTAR) observations of NY Lup and V1223 Sgr. The broadband X-ray Chandra/HETG and NuSTAR spectra are fitted by the complex absorption model $zxipab$, which is described in detail in the Appendix. We discuss these results in Section 3.

2. Observations and Analysis

V1223 Sgr and NY Lup have been observed by Chandra’s Advanced CCD Imaging Spectrometer (ACIS) and HETG (Canizares et al. 2005). HETG consists of two transmission gratings, Medium Energy Grating (MEG) and High Energy Grating (HEG), having absolute wavelength accuracies of 0.0006 Å and 0.011 Å, respectively. To model the broadband X-ray spectra, we use NuSTAR observations of V1223 Sgr and NY Lup, which have been previously analyzed by Mukai et al. (2015) and Hayashi et al. (2021). NuSTAR (Harrison et al. 2013) carries two co-aligned Wolter I telescopes that focus X-rays between 3 and 79 keV onto two independent solid-state Focal Plane Modules (FPMA and FPMB). Table 1 gives a summary of the X-ray observations of V1223 Sgr and NY Lup used in this paper.

The Chandra/HETG observations were downloaded from the Chandra archive and were processed by CIAO 4.12 and CALDB 4.9.4. The spectral products, response matrices, and ancillary files for different grating orders were obtained by running the CIAO tool chandra_repro. The positive and negative diffraction first-order spectra and their corresponding response files were co-added using the CIAO tool combine_grating_spectra. The first-order spectra extracted from the multiple Chandra/HETG observations of NY Lup were also co-added using the CIAO tool combine_grating_spectra. The NuSTAR data were processed by NuSTARDAS with the latest CALDB files. The source region was defined using a 100″ circular region and the background region was also defined using a 100″ circular region in a source-free region on the same detector. The spectral products, response matrices, and ancillary files were obtained by nuproducts. The NuSTAR spectra were grouped with grppha to have at least 30 counts per bin. Even though the NuSTAR and Chandra/HETG observations were carried out on different dates, we expect a similarity in the spectral shapes, which are determined by the gravitational potential just above the white dwarf’s surface (Shaw et al. 2018). Therefore, small changes in the overall accretion rate lead to small changes in the overall normalization without spectral variations, as seen for V2731 Oph (Lopes de Oliveira & Mukai 2019). The changes in the normalization are accounted by the cross-normalization constant of the spectral fits.

2.1. Simultaneous X-Ray Spectral Fitting of the Chandra/ HETG and NuSTAR Spectra

The post-shock plasma in many mCVs can be well represented by a cooling flow model (Done et al. 1995; Mukai et al. 2003), which contains a bremsstrahlung continuum and collisionally excited emission lines from a range of temperatures, with a distribution of emission measures appropriate for an isobarically cooling plasma. Along with a multi-temperature plasma and photoionized emission lines, there are strong spectral signatures of reflection detected for NY Lup and V1223 Sgr (Mukai et al. 2015). Hayashi et al. (2021) also studied reflections in V1223 Sgr using Suzaku and NuSTAR data using their own model consisting of multi-temperature emission and a reflection component.

The broadband Chandra/HETG and NuSTAR X-ray spectra of NY Lup and V1223 Sgr are fitted with a cooling flow model for the primary emission (mkflow in XSPEC), a reflection model for the spectral signatures of a Compton hump (reflect in XSPEC), and a complex absorption model. The X-ray spectra, especially at lower energies, are modified by a complex distribution of absorbers in the pre-shock flow, which can be represented as a power-law distribution of neutral absorbers ($pwab$ in XSPEC) (Done & Magdziarz 1998). However, the X-ray emission is capable of ionizing the pre-shock flow, hence we expect these complex absorbers to be ionized. Therefore we developed a $zxipab$ model as a local model in XSPEC, which is a power-law distribution of ionized absorbers. The complex ionized absorber model $zxipab$ is similar to $pwab$ except the ionization parameter log xi gives an indication of the degree of ionization of the absorbers in the pre-shock region. The details of the $zxipab$ model are given in the Appendix. We fit the
Chandra/HETG spectra of NY Lup and V1223 Sgr with the ionized absorber zxipab model and compare it with the fits using a neutral absorber pwab model. A Gaussian line was used to model the Fe K$\alpha$ line in the spectra, along with a Gaussian smoothing model gsmooth to account for velocity broadening of the emission lines. The power of the energy for sigma variation ($\alpha$) of the gsmooth model is fixed to 1.0. In our spectral fits to the data, we do not detect significant interstellar absorption. This may be because the interstellar column density $N_H$ for these objects is too low to be securely detected in the spectral fits, given the complexity of the source spectrum and the calibration of the time-dependent, low-energy effective area of Chandra/HETG/ACIS-S. The upper limits on interstellar absorption toward NY Lup is $1.4 \times 10^{21}$ cm$^{-2}$ (de Martino et al. 2008) and for V1223 Sgr it is $1 \times 10^{21}$ cm$^{-2}$ (Beuermann et al. 2004).

In XSPEC notation, the model is written as:

$$\text{constant}\times\text{complex}\times\text{gsmooth}$$

where complex is $\text{pwab}$ or $\text{zxipab}$. Figure 1 is a plot of model spectra obtained using $\text{zxipab}$ and $\text{pwab}$ as complex absorption models for V1223 Sgr with a log xi of 0.5.

We see a difference in the predictions between these two complex absorption models at energies below 0.8 keV, along with the presence of absorption lines in the model spectra using an ionized absorber $\text{zxipab}$ model. Due to the limited effective area and energy resolution of Chandra/HETG, we are unable to see these absorption lines in the spectra as well as the difference in the model predictions of fluxes by $\text{zxipab}$ and $\text{pwab}$, especially below 0.5 keV. As shown later in Section 2.2, we see presence of various photoionized emission lines in the Chandra/HETG spectra of NY Lup and V1223 Sgr.

The Chandra/HETG spectra were fit in the energy range 0.5–7.5 keV and the NuSTAR/FPMA + FPMB spectra in the 3–40 keV energy range. A constant was added so we could perform a simultaneous Chandra/HETG and NuSTAR/FPMA + FPMB spectral fit to account for cross-normalization differences between the different instruments. We used chi-square statistics when fitting the Chandra/HETG and NuSTAR data in XSPEC v12.11.0. The abundance table from Asplund et al. (2009) was used. The abundances of the cooling flow model were linked to the reflection model and were allowed to vary during the fit. The lowest temperature to which the plasma cools ($kT_{\text{min}}$ of the mckflow model) was fixed to a hard limit of 80.8 eV and the spectrum was calculated by using AtomDB data (switch = 2 in the mckflow model). The inclination angle of the reflecting surface of the reflect model is fixed to cos $\mu = 0.45$. The values of the spectral parameters obtained by the spectral fits to only the NuSTAR data of NY Lup and V1223 Sgr are similar to those reported by Mukai et al. (2015). Table 2 gives the spectral parameters of the best fits to the combined Chandra/HETG and NuSTAR spectra using the two complex absorption models $\text{pwab}$ and $\text{zxipab}$. The errors are calculated at the 90% confidence limit.

Figure 2 compares the complex absorption models $\text{pwab}$ and $\text{zxipab}$ with the Chandra/HETG spectra of NY Lup and $\text{V1223 Sgr}$.

### Table 2

| Parameters | NY Lup $\text{pwab}$ | $\text{zxipab}$ | V1223 Sgr $\text{pwab}$ | $\text{zxipab}$ |
|------------|-----------------------|-----------------|-------------------------|-----------------|
| $C_{\text{FPMA}}$ | $0.94 \pm 0.01$ | $0.94 \pm 0.01$ | $0.804 \pm 0.005$ | $0.805 \pm 0.005$ |
| $C_{\text{FPMB}}$ | $0.95 \pm 0.01$ | $0.94 \pm 0.01$ | $0.798 \pm 0.005$ | $0.810 \pm 0.006$ |
| $\sigma$ (gsmooth; at 6 keV) | $0.011 \pm 0.003$ | $0.011 \pm 0.003$ | $0.011 \pm 0.004$ | $0.011 \pm 0.004$ |
| $N_{\text{Hmax}}$ ($10^{22}$ cm$^{-2}$) | $15.2^{+3.0}_{-1.7}$ | $38^{+5}_{-4}$ | $15.3 \pm 0.5$ | $15.8 \pm 0.7$ |
| $\beta$ | $-0.8 \pm 0.01$ | $-0.81 \pm 0.02$ | $-0.51 \pm 0.01$ | $-0.46 \pm 0.01$ |
| log xi | $...$ | $1.3 \pm 0.2$ | $...$ | $0.5 \pm 0.1$ |
| rel_ref (reflect) | $1.6 \pm 0.2$ | $1.3^{+0.3}_{-0.1}$ | $0.9 \pm 0.1$ | $0.7 \pm 0.1$ |
| abundance | $1.1 \pm 0.2$ | $1.3 \pm 0.2$ | $0.47 \pm 0.05$ | $0.45 \pm 0.05$ |
| $kT_{\text{max}}$ (mckflow; in keV) | <73 | <78 | 41 $\pm 2$ | 42 $\pm 2$ |
| Normalization (mckflow; in $M_\odot$ yr$^{-1}$) | $(8.9 \pm 0.5) \times 10^{-10}$ | $(9.5^{+0.04}_{-0.02}) \times 10^{-10}$ | $(5.7 \pm 0.2) \times 10^{-9}$ | $(5.9 \pm 0.2) \times 10^{-9}$ |
| Fe K$\alpha$ (in keV) | $6.43 \pm 0.03$ | $6.42 \pm 0.03$ | $6.39 \pm 0.02$ | $6.39^{+0.01}_{-0.00}$ |
| Normalization (photons cm$^{-2}$ s$^{-1}$) | $(1.2 \pm 0.1) \times 10^{-4}$ | $(1.1 \pm 0.1) \times 10^{-4}$ | $(1.2 \pm 0.2) \times 10^{-4}$ | $(1.2 \pm 0.2) \times 10^{-4}$ |
| $\chi^2$ | 1265.46 for 1614 d.o.f. | 1267.50 for 1613 d.o.f. | 1838.22 for 1898 d.o.f. | 1811.80 for 1897 d.o.f. |
| Absorbed Flux (0.3–8.0 keV) | $3.1 \times 10^{-11}$ erg s$^{-1}$ | $3.2 \times 10^{-11}$ erg s$^{-1}$ | $9.8 \times 10^{-11}$ erg s$^{-1}$ | $9.7 \times 10^{-11}$ erg s$^{-1}$ |
| Absorbed Flux (3.0–40.0 keV) | $8.9 \times 10^{-11}$ erg s$^{-1}$ | $9.0 \times 10^{-11}$ erg s$^{-1}$ | $21.4 \times 10^{-11}$ erg s$^{-1}$ | $21.4 \times 10^{-11}$ erg s$^{-1}$ |

**Note.** The errors on the parameters are estimated using 90% confidence limits.
We see a sharp discontinuity at the OVII edge around $\sim 0.9$ keV in the Chandra/HETG spectra, which indicates the presence of warm absorber features (Mukai 2017). Although the ionizations parameter for NY Lup and V1223 Sgr are not very large, we still expect the pre-shock flow to be ionized due to the high X-ray fluxes from these systems. The ionized absorber model $\text{zxipab}$ is shown to fit the Chandra/HETG data better than the neutral absorber $\text{pwab}$ model, especially at lower energies. However due to the limited sensitivity of Chandra/HETG below 0.5 keV, we do not see a significant change in the fitting statistics between the two complex absorber models as expected from Figure 1.

We see residuals to the fits at lower energies in the lower panel of Figure 2. This soft excess is less for the ionized absorber model compared to the neutral absorber model. Some of these residuals are from the photoionized emission lines whose fluxes do not match the model predictions of the cooling flow model, described in detail in Section 2.2. We fit this soft excess with a blackbody component and find that the estimated temperature is higher than the previously estimated temperature of 60 eV (Evans & Hellier 2007; Anzolin et al. 2008), which is explained in the 3. However the F-test shows this blackbody is not statistically significant as a fit to this soft excess.

2.2. Photoionized Emission Lines

Figure 3 shows the MEG summed first-order spectra of NY Lup and V1223 Sgr, displaying emission lines along with their predictions from the cooling flow $\text{mkcflow}$ model. We see the presence of H- and He-like ion emission lines from Ne, Mg, Al, Si, Ar, and S in the MEG spectra of NY Lup and V1223 Sgr. We also see emission lines corresponding to the H- and He-like ions of O for V1223 Sgr, which are not seen for NY Lup, most likely due to the decreased low-energy effective area of ACIS in the 2016 Chandra HETG observation of NY Lup. We find the model predictions of the line strengths from the $\text{mkcflow}$ model describe the fluxes of most of the emission lines, except for certain He-like triplets of Si, Mg XI, Ne IX, and O VII.

Figure 4 shows the MEG first-order summed spectra of NY Lup around the Mg XI, Si XIII, and Ne IX emission lines. We can resolve the He-like triplet lines of the Ne IX emission lines, which are fitted with three Gaussian lines in the plot. For Mg XI and Si XIII, we can only resolve two lines out of the expected
He-like triplets, due to the low statistics of the third line. These are fitted with two Gaussian lines in the plot. Figure 5 shows the MEG first-order summed spectra of V1223 Sgr around the Mg XI, Ne IX, and O VII emission lines. We can resolve the He-like triplet lines of Mg XI, which are fitted with three Gaussian lines in the plot. For Ne IX and O VII, we can only resolve two lines out of the expected He-like triplets due to the low statistics of the third line. These are fitted with two Gaussian lines in the plot. In all these plots, the primary emission is fitted by a first-order polynomial plus the Gaussians for the emission lines. To estimate the excess X-ray fluxes of these emission lines which are resolved into double or triple lines, we fit them with a Gaussian line and estimate their excess flux over the predictions from the mckflow model. Tables 3 and 4 shows the excess X-ray fluxes of these photoionized lines over their flux predictions by the mckflow model. The errors are calculated at 90% of the confidence limit on the normalization of the Gaussian lines used to model these emission lines, which are propagated to account for the errors on the fluxes.

Figure 6 shows the HEG summed first-order spectra around the Fe lines of NY Lup and V1223 Sgr, where the emission lines correspond to neutral Fe (Fe Kα), He-like Fe (Fe XXV), and H-like Fe (Fe XXVI). The primary emission is modeled with the cooling flow model mckflow and a Gaussian line for Fe Kα.

Our complete fitting results using a spectral model with an ionized absorber model zzipab, cooling flow model mckflow, reflection component reflect, and Gaussian emission lines for the Fe Kα line and the emission lines described in Section 2.2 whose observed fluxes do not match the cooling flow model predictions, are shown in Figure 7 along with their residuals for NY Lup and V1223 Sgr.

3. Discussion

A previous study by Mukai et al. (2003) classified the Chandra/HETG spectra of seven CVs into two groups based on their X-ray spectra. EX Hya, V603 Aql, U Gem, and SS Cyg were classified as cooling-flow type since their X-ray spectra were described well using the mckflow model, which was originally developed to model the cooling flows in clusters of galaxies (Mushotzky & Szymkowiak 1988). In these four CVs, the cooling flow model provided a good explanation for the continuum shape as well as the strong H- and He-like emission lines of O, Ne, Mg, Al, Si, S, and the entire Fe L complex (Figure 1 in Mukai et al. 2003). On the other hand, in the three other CVs studied by Mukai et al. (2003) (V1223 Sgr, AO Psc, and GK Per), the continuum was much harder than what the cooling flow model mckflow predicted; the details of the observed emission lines were also different from the mckflow predictions. Specifically, the Fe L lines were weaker than expected, and the ratio of fluxes of He-like ions to those of H-like ions were higher than predicted. These discrepancies led Mukai et al. (2003) to explain the entire Chandra/HETG spectra of these three CVs using a photoionization model.
However, there are several issues with this interpretation. First, it is difficult to imagine a situation where the modest luminosity (of order $10^{34} \text{ erg s}^{-1}$) of these CVs can nevertheless produce H-like and He-like lines of Fe through photoionization. Second, the hard power-law continuum of Mukai et al. (2003)'s model was an ad-hoc assumption, incompatible with our standard understanding that the strong shock is the primary source of emission in IPs. Various studies (including Mukai et al. 2015) focusing on the harder end of the X-ray spectra of these “photoionized” CVs have already demonstrated that they can be modeled by a cooling flow spectra modified by a complex distribution of absorbers in the pre-shock region. Such models attribute the H-like and He-like emission lines of Fe to collisionally excited, multi-temperature, post-shock plasma. They explain the hard power-law-like continuum as that of multi-temperature, bremsstrahlung emission hardened by the complex absorber (see Appendix for an analytical understanding of this).

Given the specific accretion rate (accretion rate per unit surface area) $\dot{m}$, and assuming a shock very close to the stellar surface, we can estimate both the density of the pre-shock flow and the photon flux through this region. The pre-shock density is $\dot{m}$ divided by the free-fall velocity. For a 0.8 $M_\odot$ white dwarf, the free-fall velocity is $5.5 \times 10^8 \text{ cm s}^{-1}$ and the shock high density is $1.82 \times 10^{-9} \dot{m} \text{ g cm}^{-3}$, or a number density of $1.8 \times 10^{15} \dot{m} \text{ cm}^{-3}$. We can obtain the accretion luminosity per unit area by multiplying $\dot{m}$ by the gravitational potential (GM/R) of the white dwarf. For a 0.8 $M_\odot$ white dwarf, the luminosity per unit area is $1.5 \times 10^{17} \dot{m} \text{ erg s}^{-1}$, of which half will be radiated downward and converted into soft photons, so the hard X-ray luminosity is $7.5 \times 10^{16} \dot{m} \text{ erg s}^{-1}$.

| Ion       | $\lambda$ in Å | Flux ($\times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$) |
|-----------|----------------|--------------------------------------------------------|
| Si XIII i | 6.65           | 1.3 ± 0.7                                               |
| Si XIII f | 6.69           | 1.8 ± 0.7                                               |
| Mg XI r   | 9.18           | 0.9 ± 0.5                                               |
| Mg XI i   | 9.23           | 1.1 ± 0.5                                               |
| Ne IX r   | 13.24          | 0.6 ± 0.2                                               |
| Ne IX i   | 13.45          | 3.6 ± 0.9                                               |
| Ne IX f   | 13.54          | 4 ± 1                                                   |

| Ion       | $\lambda$ in Å | Flux ($\times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$) |
|-----------|----------------|--------------------------------------------------------|
| Mg XI r   | 9.18           | 2 ± 1                                                   |
| Mg XI i   | 9.23           | 4 ± 1                                                   |
| Mg XI f   | 9.34           | 1.1 ± 0.9                                               |
| Ne IX i   | 13.45          | 3 ± 2                                                   |
| Ne IX f   | 13.54          | 1.4 ± 0.9                                               |
| O VII i   | 21.61          | 2.1 ± 0.9                                               |
| O VII f   | 21.79          | 1.3 ± 0.9                                               |

![Figure 5](image-url) Chandra MEG summed first-order spectra of V1223 Sgr showing the presence of the He-like triplets of Mg XI (left panel), Ne IX (middle panel) and O VII (right panel). The Gaussian fits to the emission lines are shown in red and the predictions of the line strengths found with the mkcflow model are shown as black lines. The spectra are binned for clarity.
ionization parameter, $\xi = L/nr^2$, generalized for a cloud adjacent to an extended source of ionizing radiation, is independent of $\dot{m}$ and $\sim 40$ in the 0.8 $M_\odot$ immediately above the shock. However, the actual value will be lower due to geometrical dilution (both due to the finite shock height and finite distance above the shock front). We therefore expect the immediate pre-shock flow to be modestly, but measurably, ionized. This expectation is confirmed by the presence of photoionized emission lines and warm absorption features seen in Figures 2 and 3. This justifies our decision to develop a model for the ionized distribution of absorbers in the pre-shock region, $zxi_{pab}$ (see Appendix for the details of the model).

Figure 1 shows the model predictions of the complex absorption models $zxi_{pab}$ and $pwab$ at lower energies. There is a significant deviation between the predictions of the two models at energies of 0.8 keV. The ionized absorber model $zxi_{pab}$ shows the presence of a sharp discontinuity due to O VII edge at $\sim 0.9$ keV, which is also seen in the Chandra/HETG spectrum of V1223 Sgr (Figure 2). Due to the decreased effective area of Chandra/HETG, this is not as obvious for NY Lup. When we see X-rays escaping through a pre-shock region, the resulting spectrum shows warm absorber features. This pre-shock region is likely the origin of the photoionized emission lines as well. Future missions like the X-Ray Imaging and Spectroscopy Mission (XRISM) will be important for detecting the presence of warm-absorber-like absorption lines from these CVs.

The Chandra/HETG spectra of NY Lup and V1223 Sgr in Figure 3 show the presence of emission lines from the H- and He-like ions of Ne, Mg, Al, Si, S, and Fe. Many of these lines are from collisionally excited plasma, since the cooling flow model $mkcflow$ predicts the line fluxes accurately. However, the line predictions of the cooling flow model fail to account for the He-like lines of some of the medium-Z elements. These are the lines that we ascribe to photoionization. He-like triplets have a good diagnostic capability, and line ratios can be used as an independent test of line origin (collisional versus photo-ionized; Porquet & Dubau 2000; Porquet et al. 2001). However, Mukai et al. (2003) argued that this diagnostic is not appropriate for CVs, because a radial velocity gradient of thousands of km s$^{-1}$ can result in all the lines remaining completely unsaturated at all ionic column densities. This leaves the plasma in a photoexcitation-dominated regime, in which the resonance lines are stronger than in the photoionization-dominated regime (Kinkhabwala et al. 2002). Also, resonant scattering may have an important effect on the line
ratios of CVs (Terada et al. 2004). Moreover, Chandra HETG observations of CVs are far too underexposed to be able to use such diagnostics (Schlegel et al. 2014). For all these reasons, existing data cannot be used to derive a definitive origin of the lines for which the cooling flow models cannot account. The neutral Fe Kα originates both from the white dwarf surface and pre-shock flow (Ezuka & Ishida 1999).

The NuSTAR observations of NY Lup and V1223 Sgr show the presence of a Compton hump in the hard X-ray spectra and energy-dependent spin modulations with an amplitude of \( \lesssim 10\% \) (Mukai et al. 2015). Both these findings point to the fact that the shock is close to the white dwarf’s surface (a shock height of 0.05 \( R_{\text{wd}} \) for V1223 Sgr and a negligible shock height for NY Lup; see Mukai et al. 2015) resulting in strong Compton reflection off the white dwarf’s surface. This also results in strong complex absorption, and a significant degree of ionization of the pre-shock flow. All these are consequences of a high specific accretion rate \( \dot{m} \). In contrast, EX Hya has a lower \( \dot{m} \) and hence tall shocks (\( \sim R_{\text{wd}} \); where \( R_{\text{wd}} \) is radius of the white dwarf) allowing X-rays to escape the post-shock region by traveling through the sides. Hence there is an absence of complex absorption or reflection in its X-ray spectra (Luna et al. 2018).

Figure 7 shows the broadband fit of the Chandra/HETG and NuSTAR spectra of NY Lup and V1223 Sgr in the energy range 0.5–40 keV. The spectral model used for this broadband fit consists of the ionized absorber model zxipab, cooling flow model mkflow, reflection model reflect, and Gaussian lines to model the emission from Fe Kα. While just such a component is prominent in the majority of polaris, no such component was seen in IPs until Haberl & Motch (1995) discovered three “soft IPs” with such a component. Haberl et al. (2002) inferred the presence of such a component for NY Lup, with an estimated temperature of 86 eV. Since then, the presence of a soft component has been inferred for quite a few IPs (Evans & Hellier 2007; Anzolin et al. 2008). However, the high inferred blackbody temperatures of several IPs, including NY Lup, present a potentially serious problem, because the luminosities per unit area are so high that some may violate the Eddington limit, and is likely to violate the atmospheric limit (Williams et al. 1987). However previous claims of a soft component are based on spectral fits without ionized complex absorbers or photoionized emission lines. In Figure 2, we find residuals at lower energies while fitting the Chandra/HETG spectra with the complex absorber models; the residuals are lower for the zxipab model compared to the pwab model. However there are uncertainties related to interstellar absorption related to its estimation using Chandra/HETG data, and there are instrumental calibrations issues related to ACIS degradation, which could be related to these soft excesses. We attempted to fit these soft excesses with a blackbody component. However, this did not result in a statistically significant improvement of fit quality, suggesting the soft excess may not have the right shape to be explained with a blackbody component. The temperature we derive, which is unphysical for these systems, is therefore also suspect. We tentatively conclude that, when the correct spectral model is found (including an ionized complex absorber and photoionized lines), the need for a blackbody may disappear, or the blackbody temperature may not be as hot as previously claimed.

4. Summary

We have developed a new, ionized version (zxipab) of the complex absorber model pwab, and applied it, along with the cooling flow model mkflow, the reflection model reflect, and Gaussian emission lines, to Chandra/HETG and NuSTAR spectra of two IPs, NY Lup and V1223 Sgr. Our findings are as follows:

1. The ionized version provides a better, although still not a complete explanation of the spectra below 1 keV, than the neutral version.
2. We attribute the excess emission lines that cannot be explained with the absorbed cooling flow as due to photoionized emission from the immediate pre-shock flow, the same region that is responsible for the complex absorption.
3. Once both of these are taken into account, the soft blackbody component that was previously claimed for NY Lup may not be necessary. The previously claimed parameters of the blackbody component certainly are subject to revision.

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Software: CIAO (v4.10; Fruscione et al. 2006), XSPEC (v12.11.0; Arnaud 1996).

Appendix

Complex Ionized Absorber Model, zxipab

A.1. Analytical Considerations

We take Equation (1) of Done & Magdziarz (1998) as our starting point:

\[
S(E) = S_{\text{int}}(E)A \times \int_{N_{\text{HI},\text{min}}}^{N_{\text{HI},\text{max}}} N_{\text{HI}}^{\beta} \exp(-N_{\text{HI}}\sigma(E))dN_{\text{HI}}. \tag{A1}
\]

This assumes a power-law distribution of the covering fraction as a function of the absorbing column, i.e., \( C_f(N_{\text{HI}}) \propto N_{\text{HI}}] \), where \( A \) is a normalization such that \( \int_{N_{\text{HI},\text{min}}}^{N_{\text{HI},\text{max}}} C_f(N_{\text{HI}}) = 1.0 \). The effect of such an absorber is markedly different from that of a simple absorber. The latter results in an exponential decline in transmission at low energies, which is often the handle that allows one to fit for
$N_{\text{HI}}$. The combination of a simple absorber (e.g., from the interstellar medium) and a partial covering absorber produces two such exponential cut-offs, with a region in energy where the observed spectrum is dominated by the unabsorbed component. The effect of $p_{\text{wab}}$ is more power-law-like (see, e.g., Figure 9 of Mukai 2017).

This can be understood using the following considerations. By substituting $u = N_{\text{HI}} \sigma(E)$, we obtain:

$$T(E) \propto \sigma(E)^{-\beta-1} \int_{u_{\text{min}}}^{u_{\text{max}}} u^{\beta} \exp(-u) du,$$

(A2)

for the transmission $T(E)$. The integral can be expressed in terms of the incomplete gamma function:

$$P(a, x) = 1/T(a) \int_{0}^{x} t^{a-1} \exp(-t) dt$$

so that:

$$T(E) \propto \sigma(E)^{-\beta-1} \left[P(\beta + 1, u_{\text{max}}) - P(\beta + 1, u_{\text{min}})\right].$$

(A3)

The properties of the incomplete gamma function are well known: for a small positive value of $a$, it rises quickly from 0 to $\sim 1$. If $N_{\text{HI}}$ is sufficiently small and $N_{\text{HI}}$ is sufficiently large, there is a range of $E$ such that $P(\beta + 1, u_{\text{max}}) \sim 1$ and $P(\beta + 1, u_{\text{min}}) \sim 0$, so that:

$$T(E) \propto \sigma(E)^{-\beta-1}.$$  

(A4)

At the same time, $\sigma(E)$ itself can be approximated by a power law of $E$. For example,

$$\sigma(E) = 2.242 \times 10^{-22} (E/1\text{keV})^{-8/3} \text{cm}^{-2},$$

(A5)

is a good approximation of the photoelectric cross section of Morrison & McCammon (1983) between the O and Fe edges. Thus, the power-law distribution of the covering fraction can lead to a power-law-like, rather than exponential, low-energy cut-off.

$\sigma$ has discontinuities at the major edges. The neutral and ionized versions are different in the positions and the depths of the discontinuities. In particular, if all the K-shell electrons of lower-Z elements are ionized, $\sigma$ becomes close to 0 at low energies. In such a situation, the use of $\text{zxipab}$ is necessary, while a combination of $p_{\text{wab}}$ and an edge would provide a poor approximation for energies where $\sigma \sim 0$.

A.2. Implementation and Current Limitations

The neutral version of the model, $p_{\text{wab}}$, numerically integrates the neutral absorber model, wabs (Morrison & McCammon 1983). For $\text{zxipab}$, we replace the call to the wabs model with a pre-calculated grid of XSTAR photo-ionization models that was originally used for the partial covering warm absorber model, $\text{zxipcf}$ (Reeves et al. 2008).

The model parameters are the minimum and the maximum $N_{\text{HI}}$, the power-law index of the covering fraction (from $p_{\text{wab}}$), the ionization parameter log($\xi$), and the redshift of the absorber.

As with $p_{\text{wab}}$, $\text{zxipab}$ approximates the true differential covering fraction distribution using a power law. This is an intrinsic limitation of the model. A more realistic model of the pre-shock flow absorption in mCVs should replace the power law with a more realistic function, although this could rapidly expand the number of free parameters that describe it, e.g., the shape of the footpoint of the accretion curtain. Also, $\text{zxipab}$ assumes a single log($\xi$) for the absorber, whereas a realistic absorber model would also include a distribution of log($\xi$) as a function of distance from the shock front. Finally, $\text{zxipab}$ assumes an absorber with solar abundances, which is not guaranteed to hold for all mCVs, particularly for those with a nitrogen abundance (see, e.g., the case of V2731 Oph; Lopes de Oliveira & Mukai 2019).

$\text{zxipab}$ is available as a new model in XSPEC through this website.\(^5\)

\(^5\) https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/newmodels.html

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