PHOTOIONIZED FEATURES IN THE X-RAY SPECTRUM OF EX HYDRAE

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ABSTRACT

We present the first results from a long (496 ks) Chandra High Energy Transmission Grating observation of the intermediate polar EX Hydræ (EX Hya). In addition to the narrow emission lines from the cooling post-shock gas, for the first time we have detected a broad component in some of the X-ray emission lines, namely, O viii λ18.97, Mg xii λ8.42, Si xiv λ6.18, and Fe xvii λ16.78. The broad and narrow components have widths of ~1600 km s\(^{-1}\) and ~150 km s\(^{-1}\), respectively. We propose a scenario where the broad component is formed in the pre-shock accretion flow, photoionized by radiation from the post-shock flow. Because the photoionized region has to be close to the radiation source in order to produce strong photoionized emission lines from ions such as O viii, Fe xvii, Mg xii, and Si xiv, our photoionization model constrains the height of the standing shock above the white dwarf surface. Thus, the X-ray spectrum from EX Hya manifests features of both magnetic and non-magnetic cataclysmic variables.

Key words: binaries: close – novae, cataclysmic variables – stars: individual (EX Hydræ) – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

EX Hydræ (EX Hya) belongs to a sub-class of magnetic cataclysmic variables (CVs), known as intermediate polars (IPs), wherein the white dwarf (WD) magnetic field (~0.1–10 MG) channels material from the inner edge of the truncated accretion disk through the accretion curtains and accretion columns to spots near the magnetic poles (Rosen et al. 1988). In this model, the channeled material reaches supersonic velocities in the pre-shock flow (\(v_{\text{ff}} = (2GM_{\text{WD}}/R_{\text{WD}})^{1/2} \sim 6000\) km s\(^{-1}\), where \(v_{\text{ff}}\) is the free-fall velocity for a WD of mass \(M_{\text{WD}} = 0.79\) \(M_{\odot}\) and radius \(R_{\text{WD}} = 7.1 \times 10^{8}\) cm) before passing through a strong stand-off shock near the WD surface. At the shock, the kinetic energy is converted into thermal energy, heating the gas to temperatures of ~20 keV (Fujimoto & Ishida 1997; Brunschwiger et al. 2009). Below the shock, in the post-shock flow, the cooling material radiates its thermal and residual gravitational energy through free–free, bound–bound, and free–bound radiation, which is primarily detected in X-rays.

The nature of the observed X-ray spectrum depends primarily on the specific accretion rate (i.e., the accretion rate per unit area). The small spot size and hence high specific accretion rate of magnetic CVs impose a conical geometry that does not allow the X-ray photons to escape without further interaction. Thus, the observed spectrum is dominated by emission lines formed in a region photoionized by the radiation field from the shocked region. In contrast, the boundary layer at the inner edge of the accretion disk of non-magnetic CVs covers a relatively large area and therefore the specific accretion rate is low, allowing X-rays to escape freely. Mukai et al. (2003) observed this “binomial” distribution in moderately exposed (~100 ks) observations obtained with Chandra using the High Energy Transmission Grating (HETG) and generally found that the X-ray spectra of magnetic CVs are compatible with photoionized emission while those of non-magnetic CVs are consistent with a collisionally ionized, cooling gas (modeled as a cooling-flow in X-ray spectral fitting packages such as XSPEC\(^{6}\)). Interestingly, EX Hya was the “exception” of the distribution: its X-ray spectrum was well fit with a cooling-flow model. This can be explained if EX Hya has a tall shock (Allan et al. 1998b), a lower accretion rate, and/or larger accretion spots than other IPs, and therefore a low specific accretion rate, leading to a dominant collisionally ionized, cooling spectrum.

We have obtained a deeper observation of EX Hya with Chandra in order to study a number of accretion-related phenomena. In this paper, we present new results from this observation discussed in Section 2. In Section 3, we present an analysis of the line profiles that require a broad component, and a photoionization model to explain it. Discussion and conclusions are presented in Section 4.

2. OBSERVATIONS

EX Hya was observed with Chandra using the HETG in combination with the ACIS-S for 496 ks. The observation was obtained in four segments (ObsIDs 7449: start time 2007 May 13 22:15:35 UT, exposure time 130.65 ks; 7452: start time 2007 May 17 03:12:38 UT, exposure time 49.17 ks; 7450: start time 2007 May 18 21:56:57 UT, exposure time 162.73 ks; and 7451: start time 2007 May 21 14:15:08 UT, exposure time 153.07 ks). We extracted High-Energy Grating (HEG) and Medium-Energy Grating (MEG) ± first-order spectra and Ancillary Response Matrices (ARFs) using the CIAO\(^{7}\) script fullarf, while Response Matrix Functions (RMFs) were extracted using the mkarf script. We combined ARFs and spectra from each segment using the add_grating_spectra script. For Si xiv λ6.18 and Mg xii λ8.42, fits were performed...
using the HEG and MEG ± first-order data, whereas for Fe xvi \( \lambda 16.78 \) and O viii \( \lambda 18.97 \) we used only MEG ± first-order data, due to the rapid decay of the HEG effective area for \( \lambda > 17 \text{ Å} \) (Chandra Proposer’s Observatory Guide v11.0, POG).

3. EMISSION-LINE PROFILES

3.1. Line Profiles Analysis

In order to test models of the cooling of the post-shock gas (e.g., Aizu 1973; Canalle et al. 2005), we measured the fluxes of the strong emission lines observed in the HETG spectrum using a Gaussian to represent each emission line and a first-order polynomial to represent the nearby continuum. We found that some of the strong emission lines were poorly fit with such a model and acceptable fits, in particular for O viii \( \lambda 18.97, \) Fe xvi \( \lambda 16.78, \) Mg xii \( \lambda 8.42, \) and Si xiv \( \lambda 6.18, \) could be obtained by adding a second Gaussian to represent the broad-line wings. All the parameters were free to vary, and their limits were determined to 90% confidence. Figure 1 shows these emission lines together with the best-fit models. Central wavelength, full width half maximum (FWHM), and observed flux of the narrow and broad components are listed in Table 1.

An instrumental origin for these broad emission lines seems unlikely. First, the broad component is detected in four spectral orders simultaneously (HEG and MEG ± 1), whereas any broadening in the dispersion direction of a diffraction arm should not affect the dispersion in another arm. Second, as shown in Figure 2, a comparison with a similarly deeply exposed observation of the pre-main-sequence star TW Hya (exposure time: 489 ks; Brickhouse et al. 2010) with the same instrument configuration does not show similar broad features.

The statistical significance of the presence of a broad component in the line profiles was assessed by fitting 10,000 Monte Carlo realizations of the spectra in the neighborhood of each line, using a model consisting of a continuum plus a single Gaussian, with the same exposure time, RMFs, and ARFs as our observation, following the method described in Protassov et al. (2002) and Reeves et al. (2003). We fit the simulated spectra using two models: a continuum plus (1) a single Gaussian (with a total of four free parameters, resulting in: \( \chi^2(\text{O viii}) = 503.70; \) \( \chi^2(\text{Mg xii}) = 1671.69; \) \( \chi^2(\text{Si xiv}) = 868.04; \) and \( \chi^2(\text{Fe xvi}) = 162.72 \) and (2) two Gaussians (with a total of seven free parameters, resulting in: \( \chi^2(\text{O viii}) = 398.60; \) \( \chi^2(\text{Mg xii}) = 1577.30; \) \( \chi^2(\text{Si xiv}) = 772.40; \) and \( \chi^2(\text{Fe xvi}) = 141.77 \)). The difference in \( \chi^2 \) between the fit of the double- and single-Gaussian models

![Figure 1. Observed emission-line profiles with overlaid double-Gaussian models of (a) and (e) O viii \( \lambda 18.97 \) (HEG ±1), (b) and (f) Fe xvi \( \lambda 16.78 \) (HEG ±1), (c) and (g) Mg xii \( \lambda 8.42 \) (HEG ±1), and (d) and (h) Si xiv \( \lambda 6.18 \) (HEG ±1). Data are shown by the black histograms and the narrow, broad, and net components of the model profiles are shown by the green, blue, and red histograms, respectively. The two emission lines (Fe xvi–xxi \( \lambda 8.31 \) and Fe xxiv \( \lambda 8.38 \)) in the vicinity of Mg xii \( \lambda 8.42 \) were included in the fit. Below each panel, we plot the residuals relative to the net double-Gaussian model (red) and to its narrow component (green). (A color version of this figure is available in the online journal.)](image-url)
seen in EX Hya is not of instrumental origin. The broad component in the TW Hya line profile demonstrates that the broad component excess emission in the wings of the EX Hya line profile. The lack of a broad component could be produced purely by random, Poisson noise. We found that only 1–10 in 10,000 of the randomly generated single-Gaussian spectra could produce a similar decrease to the data was computed for each spectrum in order to test if the broad component is the most likely source of the observed broad components of the X-ray emission lines of EX Hya.

In principle either photoionization or collisional excitation could produce the observed broad components; however, if the width is interpreted as thermal broadening ($T_{\text{ion}} = 1.69 \times 10^9 \times \mu \times [\Delta \lambda_{\text{FWHM}}/\lambda]^2$, where $T_{\text{ion}}$ is the ion temperature in eV, $\mu$ is the ion mass, $\Delta \lambda_{\text{FWHM}}$ is the observed FWHM of the line, and $\lambda$ is the observed central wavelength), the measured widths imply temperatures $T_{\text{ion}} \sim 80$ keV, much higher than the measured peak electron temperature $T_e \sim 20$ keV (Fujimoto & Ishida 1997; Brunschwager et al. 2009). On the other hand, a photoionization origin for the broad emission lines is possible if there is a region in the system that fulfills certain conditions. First, ionization parameters ($\xi = L_X/n r^2$, where $L_X$ is the X-ray luminosity, $n$ is the number density, and $r$ is the distance between the source and target of the photoionizing flux) of a few hundred are required to account for the presence of O viii, Mg xii, and Si xiv (e.g., Kallman & McCray 1982). Second, the emission measure (EM = $n^2 V$, where $V$ is the volume) of the photoionized plasma must be large enough to produce the observed flux.

The conditions above exclude the accretion curtains and favor the pre-shock flow as the source of the broad X-ray emission lines. Consider first the accretion curtains: using the observed O viii luminosity at an inner disk radius of $10 R_{\text{WD}}$ (e.g., Beuermann et al. 2003) and with an ionization parameter of a few hundred results in a density $\sim 3 \times 10^{10}$ cm$^{-3}$, and hence a volume $\sim 2 \times 10^5 R_{\text{WD}}^3$, which is hundreds of times the volume available at that distance from the WD. Consider next the pre-shock flow: at a distance of $0.1 R_{\text{WD}}$, the same ionization parameter and luminosity imply a density $\sim 3 \times 10^{14}$ cm$^{-3}$, and hence a volume $\sim 0.002 R_{\text{WD}}^3$ which is roughly the size of the accretion shock region.

Given these considerations, we constructed a model of the X-ray line emission from the photoionized flow above the shock. We assumed a WD of mass $M_{\text{WD}} = 0.79 M_\odot$ (Beuermann &

we measured large widths in the broad components, which imply that the radiating plasma is moving with large velocities ($v \gtrsim 2000$ km s$^{-1}$). Of the three regions of the magnetically controlled accretion flow—the accretion curtains, where the flow rises up and away from the truncated accretion disk; the pre-shock flow, where the relatively cool flow falls with high velocity toward the WD surface; and the post-shock flow, where the hot, low-velocity flow settles onto the WD surface—the pre-shock flow is the most likely source of the observed broad components of the X-ray emission lines of EX Hya.

3.2. The Photoionization Model

The width of the broad component allows us to constrain the region where the line is formed. As listed in Table 1, to the data was computed for each spectrum in order to test if the broad component could be produced purely by random, Poisson noise. We found that only 1–10 in 10,000 of the randomly generated single-Gaussian spectra could produce a similar decrease in $\chi^2$ when compared to the observed data, after the addition of a broad emission line (see Table 1 and Figure 3). The null hypothesis probability that the broad component could arise purely from Poisson noise is $\lesssim 0.1\%$; thus, the broad components are detected at 99.9% confidence.

### Table 1

| Line | Narrow Component | | Broad Component |
|---|---|---|---|
| $\lambda$ (Å) | FWHM$^b$ (km s$^{-1}$) | Flux$^d$ | $\lambda$ (Å) | FWHM$^c$ (km s$^{-1}$) | Flux$^d$ |
| O viii λ18.97 | 18.972$^{+0.006}_{-0.006}$ | 315$^{+25}_{-25}$ | 7.13$^{+0.3}_{-0.3}$ | 18.972$^{+0.011}_{-0.011}$ | 1927$^{+1220}_{-162}$ | 2.77$^{+0.3}_{-0.3}$ |
| Fe xvi λ16.78 | 16.777$^{+0.024}_{-0.012}$ | 117$^{+42}_{-50}$ | 2.75$^{+0.18}_{-0.15}$ | 16.783$^{+0.019}_{-0.018}$ | 1963$^{+1247}_{-511}$ | 0.55$^{+0.19}_{-0.21}$ |
| Mg xii λ8.42 | 8.429$^{+0.006}_{-0.006}$ | 360$^{+34}_{-34}$ | 1.08$^{+0.09}_{-0.08}$ | 8.424$^{+0.006}_{-0.006}$ | 1329$^{+176}_{-108}$ | 0.53$^{+0.10}_{-0.09}$ |
| Si xiv λ6.18 | 6.185$^{+0.006}_{-0.006}$ | 410$^{+57}_{-57}$ | 1.09$^{+0.03}_{-0.10}$ | 6.185$^{+0.006}_{-0.006}$ | 1297$^{+21}_{-78}$ | 0.84$^{+0.03}_{-0.05}$ |

### Notes.

*a O viii and Fe xvi were fit using only the MEG arm; Mg xii and Si xiv were fit using both the HEG and MEG arms.*

*b Absolute wavelength accuracy: HEG = 0.006 Å, MEG = 0.011 Å. Relative wavelength accuracy: HEG = 0.0010 Å, MEG = 0.0020 Å (Chandra POG).*

*c FWHM $\approx 2.35$σ.*

*d Units of $10^{-4}$ photons cm$^{-2}$ s$^{-1}$.

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![Figure 2](example.png)

**Figure 2.** Upper panel: observed O viii λ18.97 emission-line profile in EX Hya (black) and TW Hya (red), scaled to the same peak intensity. Lower panel: relative difference between the EX Hya and TW Hya profiles, showing the excess emission in the wings of the EX Hya line profile. The lack of a broad component in the TW Hya line profile demonstrates that the broad component seen in EX Hya is not of instrumental origin.

(A color version of this figure is available in the online journal.)
of the accretion spot on the surface of the WD in units of the WD radius,
\[ \tau_e \approx \frac{R}{\rho} \left( \frac{R_{\text{WD}}}{r} \right)^{-3/2} \]
where \( \rho \) is the pre-shock density. With this assumption, the flux of the illuminating radiation and hence the ionization parameter drop rapidly just above the shock on a length scale comparable to the shock size. The atomic physics packages described in Miller et al. (2008) are used to compute the ionization and thermal equilibrium and the attenuation of radiation along and perpendicular to the column axis. We have explored four different models—designated A, B, C, and D—that were chosen to match the observed \( L_X \), and differ only in the area of the accretion spot. The resulting parameters of each model, listed in Table 2, are the pre-shock density \( n_0 \), the optical depth for electron scattering \( \tau_e \), the size of the accretion spot \( r_{\text{spot}} \), the shock height \( h_{\text{shock}} \), the height of the \( \text{O vii} \) peak emissivity \( d \), and the observed flux of the broad lines.

The corresponding radiative recombination continua should be comparable in strength to the predicted line fluxes, but they will be significantly smeared in wavelength and therefore difficult to detect. The models are quite simple in that they include only one-dimensional radiative transfer and neglect time-dependent ionization, compressional heating of the infalling gas due to the assumed dipole geometry, and density stratification in the pre-shock flow. However, our model should give the correct intensities for the strong lines. We note that the detection of a broad component in \( \text{Fe xiv} \lambda 16.78 \), but not in \( \lambda 15.01 \), supports a photoionization origin. Liedahl et al. (1990) predict \( \text{Fe xiv} \lambda 16.78/\text{Fe xii} \lambda 15.01 > 25 \) at densities of \( 10^{13} \) cm\(^{-3} \), with the ratio of both lines increasing with density.

It should be noted, however, that the tabulated densities are comparable to the post-shock densities derived by Mauche et al. (2001, 2003) from the \( \text{Fe xvi} \) and \( \text{Fe xxii} \) emission-line ratios, whereas the post-shock density should be higher by a factor of 4 due to shock compression and by an additional factor due to compression as the shocked gas cools. The latter would be an order of magnitude for a steady flow, but could be much smaller due to the thermal instability of radiative shocks (Chevalier & Imamura 1982).

### 4. DISCUSSION AND CONCLUSIONS

Our photoionization models (A–D) yield fluxes for \( \text{O vii} \) in good agreement with the observed value, but the predicted \( \text{Fe xvi} \), \( \text{Mg xii} \), and \( \text{Si xiv} \) fluxes are smaller by a factor of 2–30. Although our simple model is not accurate in the prediction of all the observed fluxes, it is appropriate in the sense that it shows that very small spots require higher pre-shock densities than those observed by Mauche et al. (2001, 2003) for the post-shock flow, and very large accretion spots give small ionization parameters that cannot produce the observed flux. Furthermore, comparison of the free-fall velocity with the FWHM indicates that the accretion column must not be too far from the limb of the WD as seen from Earth. The model predicts that the Doppler width \( (v \approx 2000 \text{ km s}^{-1} ) \) of the ionized material is smaller than the ~6000 km s\(^{-1} \) free-fall velocity, which would be seen if the columns were observed face-on. The smaller observed line width suggests that the accreting poles remain in the vicinity of the WD limb as seen from Earth, as supported by the small spin-phase radial velocity variations observed by Hoogerwerf et al. (2005) and the small equivalent width (\( \text{FWHM} \sim 36 \text{ eV} \)) of the \( \text{Fe xii} \) line: George & Fabian (1991) calculated that such an EW would be observed if the angle between the line of sight and the reflecting surface is roughly 80°, i.e., the accreting poles are close to the limb.
We can decide which models are more adequate using additional arguments. First, the height of the shock should be larger than $\approx 0.015 \, R_{\text{WD}}$ to account for the observed modulation in the X-ray light curves (Allan et al. 1998; Hoogerwerf et al. 2006), but less than $\sim 2 \, R_{\text{WD}}$ to account for $T_{\text{e}} \sim 20$ keV at the shock. Second, the predicted densities should be less than the values derived by Mauche et al. (2001, 2003) from the Fe xvi and Fe xxii line ratios. Third, a significant optical depth for electron scattering implies modulations (pulse fraction $\geq 10\%$) in the light curves in the 6–8 keV range, which were observed in Ginga data by Rosen et al. (1991). Allan et al. (1998), however, found only an upper limit of 4% for the pulse fraction in the light curve in the 6–8 keV range observed with ASCA. Moreover, as detailed by Rosen (1992), the favorable lines of sight to detect a high energy modulation due to electron scattering would also imply significant photoelectric absorption in the pre-shock material, which will extinguish the low-energy flux and manifest itself as flat-bottomed X-ray curves.

Based on the above conditions, we discard models C and D because: (1) their densities are higher than those obtained by Mauche et al. (2001, 2003) line ratios; (2) the combination of high densities and small accretion spot size implies significant optical depth for electron scattering (see Table 2), predicting flat-bottomed soft X-rays light curves, which are not observed (Hoogerwerf et al. 2006; Allan et al. 1998); and (3) model D implies a small shock height, such that the collisionally ionized lines in the post-shock flow will form even closer to the WD. Such emission would not show the observed sinusoidal modulation in the light curves (Allan et al. 1998), but would show the presence of two spikes (observed in the Mg xi light curve, but not in the more highly ionized Mg xii; Hoogerwerf et al. 2006).

Models A and B are both acceptable because: (1) their densities agree with values obtained from observations (Mauche et al. 2001, 2003); and (2) the optical depth for electron scattering in Models A and B is low and its contribution to the high energy light curve modulation and absorption is small, in agreement with the absence of $\sim 100\%$ pulse fraction in the low-energy light curves and upper limit of 4% in the pulse fraction of the light curves in the 6–8 keV range observed by Allan et al. (1998).

Summarizing, we detect for the first time in X-rays a broad component in the emission-line profiles of EX Hya and suggest that its origin is related to photoionization of a region in the pre-shock flow by radiation emitted in the post-shock cooling flow. Such an origin conforms with that of the broad optical, UV, and FUV emission lines observed in EX Hya (Hellier et al. 1987; Gheenly et al. 1997; Mauche 1999; Belle et al. 2003): lines whose widths, fluxes, and radial velocities vary predominantly on the WD spin phase, which are interpreted as arising in the pre-shock flow. Even more satisfying, in two cases—O vii $\lambda\lambda 1032, 1038$ in the FUV (Mauche 1999) and N v $\lambda\lambda 1239, 1243$ in the UV (Belle et al. 2003)—narrow components that rotate with the WD are observed in the predominately broad emission lines. In fact, the most obvious difference between the O vii and N v emission lines in the FUV and UV wavebands and the O viii $\lambda 18.97$, Fe xvi $\lambda 16.78$, Mg xi $\lambda 8.42$, and Si xiv $\lambda 6.18$ emission lines in the X-ray waveband is the relative strength of the narrow and broad components. Although rather simple, our photoionization model for the origin of the broad component of the X-ray emission lines yields appropriate values for the height of the shock and the size of the accretion spot. Altogether, our observational findings and the results from our model agree with a scenario where the geometry imposed by the specific accretion rate allows most of the photons from collisional excitation to escape freely, and a small fraction of those photons to photoionize the pre-shock gas. In this regard, the X-ray spectrum from EX Hya manifests both features of the “binomial” distribution found by Mukai et al. (2003).

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