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X-ray line emission from cataclysmic variables

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Abstract

We discuss the X-ray line emission as observed with the HETG on *Chandra* of a sample of CV spectra. A portion of the data have been fit with global models by Mukai et al. [Mukai, K. et al. Two types of X-ray spectra in cataclysmic variables. ApJ 586, L77–L80, 2003]; we analyze the same spectra using a line-by-line fit. The results are similar to those reported by Mauche et al. on EX Hya, but additionally cover the other CVs. A broad range of temperatures is indicated based on the H/He-like ratio of O, Mg, S, and Fe.

Keywords: Cataclysmic variables; X-ray lines; Grating spectra

1. Introduction

Cataclysmic variables are short-period, interacting binary stars in which the primary is a white dwarf (WD) and the secondary a low-mass companion. The secondary may be a main sequence star, but evidence exists that the secondary is slightly evolved Warner (1995).

Several subclasses of CVs exist including dwarf novae, classical novae, magnetic CVs (polars, intermediate polars), and nova-likes. Based on optical observations, novae erupt once and have not been observed to recur. Dwarf novae routinely undergo outburst cycles, with cycle times typically of ∼10 s of days. Nova-likes resemble classical novae spectroscopically but have never been observed to erupt. The magnetic CVs split into two sub-types based upon the dominance of the magnetic field. For polars, the field completely dominates the accretion process; matter threads onto the field lines at or near the inner Lagrangian point and flows to the magnetic poles. In intermediate polars, the field is less dominant, so a disk may form; the conditions under which disks do form is part of an ongoing debate within the CV community.

That cataclysmic variables (CVs) emit X-rays has been known for decades; the first paper linking 'X-rays' with 'CV' is Warner (1974) and discusses soft X-ray emission from the dwarf nova SS Cyg. Accretion disks themselves are not expected to be the source of the X-rays because the potential wells of the white dwarfs are too shallow, in contrast to neutron star binaries Frank et al. (2002). A broad variety of models exist, starting with that of Aizu (1973) (qv Mukai (2003) for more details). In that model, X-ray emission is generated as matter funnels to the magnetic pole, producing a shock just above the WD's surface. Mukai (2004) and Mukai (2003) contain recent reviews of the X-ray emission of CVs.

Considerable energy has been expended by researchers over the past ∼30 years to obtain and to interpret the observations. Spectral resolution has ranged from near unity (e.g., *Einstein* and *ROSAT* High-Resolution Imagers) to moderate (*ROSAT* PSPC, *ASCA* SIS, *Chandra* ACIS, *XMM* EPIC, *Bepposax*). During this time, several instruments stand out for specific attributes: *EXOSAT*, for its

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long, uninterrupted observation period; the *ROSAT* PSPC with its low internal background and large response at very soft energies, both good for faint and soft sources typical of some CVs; the *Ginga* LAC and *RXTE*PCA, both for their broad energy coverage and large effective areas; and the *ASCA* SIS as the first CCD-based spectrometer.

Essentially, low- and moderate-resolution observations lead to measurements indicative of the column density N_H and a parameter that characterizes the continuum such as the temperature kT. Additional model components are sometimes required: Fe K line emission; a component to account for a broad bump observed above 10 keV that is attributed to reflection of the hard X-rays from the WD's surface; and varying absorption components.

Tight bounds on the sizes of the emission regions were obtained by using the available detectors as high-speed photometers. Norton and Watson (1989) demonstrated that absorption was modulated at the WD spin period and was stronger at lower energies. Among the most notable studies adopting this approach are those by Hellier (1997) and Schwope et al. (2001). Hellier observed 20 eclipse egresses of the intermediate polar XY Ari. After aligning the egresses, Hellier showed that the accretion region emerged from occultation in less than 1 s, limiting the size to <0.002 of the white dwarf's surface. Schwope et al. accumulated ~230 ks of *ROSAT* time on the eclipsing polar HU Aqr and demonstrated clear evidence for accretion rate variations of a factor of 40, eclipses by the companion star, the accretion stream, and an accretion curtain lying between the two stellar components.

2. Current status

The nature of the debate changed with the launches of *Chandra* and *XMM-Newton* because each observatory carried gratings capable of resolutions of $\Delta E/E \sim 0.02$ at 6 keV, an improvement over CCD resolutions by about a factor of ~10. This improvement permits the study of individual line contributions from a variety of ionization complexes expected in the 0.5–10 keV band, particularly in the 0.5–2 and 6.4–7.0 keV bands.

The first-order resolutions of the *Chandra* transmission gratings (the High Energy Transmission Grating = HETG = High Energy Grating + Medium Energy Grating) are of order 0.012 and 0.023 Å FWHM, respectively, while the Low-Energy Transmission Grating (LETG) delivers a resolution of ~0.05. A resolution of 0.012 Å corresponds to a velocity of ~360 km s^{-1} at 10 Å. For *XMM-Newton*, the Reflection Grating Spectrometer provides ~0.04 Å resolution in first order.

Mukai et al. (2003) studied the available *Chandra* grating observations of CVs. They compared seven HETG spectra to models and found that the spectra could be separated into two groups that they labeled 'photoionization' and 'cooling flow' based on the two models that provided the best fits to the spectra. The photoionization group showed a continuum rising toward smaller wavelengths while the cooling flow group showed enhanced line emission. While the separation is based on small numbers of spectra, the split was suggestive because the photoionization group consisted entirely of intermediate polars. Unfortunately for the cleanliness of the split, EX Hya, an intermediate polar, belonged to the cooling flow group.

In studying the results of Mukai et al. closely, our group was struck by the number of lines that were not well fit by either model. We were concerned that important line details were lost in the global fit. As a result of our review, we endeavored to approach the issue from two directions. First, we fit the spectra with multiple-component models, with the number dictated by the fit statistics. Second, we fit the lines individually. Our goals were twofold: (i) a comparison of the two approaches for consistency (were we converging on the same measures?); and (ii) what inferences could we make about temperature or densities from ratios of the individual line fits? In the material that follows, we focus on the second goal using the *Chandra* HETG observations.

To date, 11 CVs have been observed with *Chandra*: the dwarf novae SS Cyg, U Gem, SU UMa, and WX Hyi; the polar AM Her; the intermediate polars V1223 Sgr, EX Hya, AO Psc, and GK Per; and the old nova V603 Aql. Unfortunately, most of the spectra were under-exposed, with an *a priori* poor signal-to-noise ratio, particularly evident above ~18 Å where important transitions of oxygen and nitrogen are expected. For this review, we use the non-outburst spectra of the dwarf novae SS Cyg and U Gem.

Nevertheless, prior knowledge of line positions allows us to fit the spectra with multiple gaussians by fixing the model centers at the positions of known transitions. We treat the lines as unresolved (gaussian 'sigma' parameter fixed at 0.0) unless a fitted gaussian appears to require a broad line. We generally steered clear of the 10–18 Å region given the plethora of Fe lines present in this area. We did not ignore that band, but targeted particular lines for fitting, including the lines Fe XVII 15.01, 15.26, 17.05, and 17.10 Å; Fe XXII 11.43 and 11.73 Å; and Fe XXIII 11.77 and 11.92 Å.

We make one potentially critical assumption: we assume zero impact of dielectronic scattering. In spite of the excellent work by Oelgoetz and Pradhan (2001) that shows DES may dominate spectral features, we simply do not have the spectral resolution at this stage to assess the impact. We must defer that study for another day when significantly improved data are available.

One result immediately leaps from the fits: *none* of the spectral lines in the non-outburst spectra require a non-zero gaussian width. This result is counter to observations in the FUV with FUSE which show CVs with broad lines of ~1500 km s^{-1} (Barrett et al., unpublished). This contrast highlights the fundamental value of the diagnostic capability of X-ray emission lines provided we have high-resolution, time-resolved spectra.