First *XMM-Newton* observations of a Cataclysmic Variable II: spectral studies of OY Car*

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Abstract. We present *XMM-Newton* X-ray spectra of the disc accreting cataclysmic variable OY Car, which were obtained during the performance verification phase of the mission. These data were taken 4 days after a short outburst. In the EPIC spectra we find strong Iron $K\alpha$ emission with weaker Iron $K\beta$ emission together with Silicon and Sulphur lines. The spectra are best fitted with a three temperature plasma model with a partial covering absorber. Multiple temperature emission is confirmed by the emission lines seen in the RGS spectrum and the H/He like intensity ratio for Iron and Sulphur which imply temperatures of ~7keV and ~3keV respectively.

Key words: accretion, accretion discs – binaries: eclipsing – stars: individual: OY Car – novae, cataclysmic variables – X-rays: stars

1. Introduction

Cataclysmic variables (CVs) are close binary systems in which the secondary (usually a dwarf main sequence star) fills its Roche lobe and transfers material onto the white dwarf primary. In non-magnetic systems, this material forms an accretion disc around the primary. Some of these systems show 'dwarf nova' outbursts on the timescale of weeks to months when the system brightens by several magnitudes lasting a few days to months. During an outburst, the material close to the white dwarf is optically thick, while in quiescence the gas is optically thin (Pringle & Savonije 1979, Narayan & Popham 1993, Popham & Narayan 1995).

X-ray observations of dwarf novae are hampered by their relatively low flux levels. With observations using

large effective areas, such as *XMM-Newton* (Jansen et al, 2001), we can obtain high signal to noise X-ray spectra of dwarf novae for the first time. In this paper we present and analyse X-ray spectra of the dwarf nova OY Car. In a companion paper (Ramsay et al 2001), we present and analyse the light curves of OY Car.

2. Observations

Ramsay et al (2001) describe the *XMM-Newton* observations. Briefly, OY Car was observed twice using *XMM-Newton*. The first observation (29–30 June 2000) was longer (~50 ksec in duration for the EPIC detectors) and had a higher count rate than the second observations (7 August 2000). This paper concentrates on the first observation which was made 4 days after a short outburst of OY Car.

The EPIC exposures were taken in full window mode using the medium filter. The particle background in both the EPIC detectors (0.1–12keV) (Turner et al 2001) and the RGS (0.3–2.1keV) (der Herder et al 2001) increased significantly towards the end of the observation: these data were therefore removed from the analysis. Before extracting any spectra of OY Car, the raw data were processed using the *XMM-Newton* Science Analysis System released on 2000 July 12.

3. The RGS spectrum

Although the mean background subtracted count rate was low (~ $0.05\,\mathrm{ct\,s^{-1}}$) we were able to extract the RGS spectrum using data from both detectors (Figure 1). Prominent emission lines are seen at 0.654 keV from O VIII Ly α and at 1.473 keV from Mg XII Ly α. Fainter lines are seen from O VIII Lyβ at 0.775 keV and L-shell transitions of Fe XXIV to Fe XX between 1.16 keV and 0.96 keV. There is a possible detection of Si XIII He-like series around 1.854 keV. The emission line around 0.729 keV is hard to iden-

tify. It cannot be from Fe XVII or the corresponding line at 0.826 keV would also be visible.

The RGS spectrum suggests emission from a distribution of temperatures. The lack of significant emission from the O VII He-like series suggests a temperature of ~0.5keV. The detection of Fe XXIII and Fe XXIV lines suggests another emission component with a temperature of ~ 1.0 to 2.0 keV.

4. The EPIC spectra

4.1. General features

Spectra were extracted from all 3 EPIC cameras using apertures ~ $30''$ in radius centered on OY Car, chosen so that the aperture did not cover more than one CCD. This encompasses ~90 percent of the integrated PSF (Aschenbach et al 2000). Background spectra were extracted from the same CCD on which the source was detected, scaled and subtracted from the source spectra.

Since the response of the detectors is not well calibrated at present below ~0.3keV, energies below this were ignored in the following analysis. In our fits we used the response file mos1_medium_all_v3.14_15_tel2.rsp for the MOS detectors and epn_fs_Y9_medium.rmf for the PN detector. Since this PN response assumes only single pixel events, we only extracted these events to make our PN spectrum.

We show in Figure 2 the integrated EPIC PN spectrum. Strong Iron Kα emission lines are seen at ~6.70 & 6.94keV, weaker Iron Kβ line at 7.90 keV and emission from Fe-L lines around 1.1keV. Lines are also seen from Si and S. Similar lines are seen in the spectra of the disc accreting CV SS Cyg (Done & Osborne 1997) and the weakly magnetic CV EX Hya (Ishida, Mukai & Osborne 1994).

4.2. Spectral fitting

Several dwarf novae were observed using *ASCA* (0.6–10.0keV), which until the launch of *XMM-Newton* and *Chandra*, had the highest X-ray spectral resolution. Amongst the brightest dwarf novae observed using *ASCA* was SS Cyg. Done & Osborne (1997) showed that in outburst a multi-temperature model was needed, while in quiescence a single-temperature model gave good fits to the data. We therefore fitted all three integrated EPIC spectra simultaneously using models of increasing complexity.

Using a single temperature thermal plasma model and a model for absorption by neutral gas (the MEKAL and WABS models in XSPEC) we obtained a fit with χ^2_ν=2.23 (890 d.o.f.) with a best fit temperature of kT=6.1keV. Adding a second thermal plasma model we obtained a significantly better fit: χ^2_ν=2.06 (888 d.o.f.) (kT=3.3, 8.0keV). The normalisation of the various emission components was allowed to vary between the three EPIC spectra although their

relative normalisations were the same in each spectrum. Adding a third plasma model gave χ^2_ν=1.87 (886 d.o.f.) (kT=0.8, 3.3, 7.7keV). Using an F-test this model is better than the previous with a significance greater than 99.99 percent. The addition of yet another thermal plasma component did not give a significantly better fit nor did the addition of a blackbody component.

We note the lack of line emission at 6.4keV. A line at 6.4keV has been seen in some dwarf novae (eg SS Cyg observed using *ASCA*: Done & Osborne 1997) which is due to fluorescence either from the surface of the white dwarf or surrounding local material. The fact that we did not see a fluorescent line is possibly due the high inclination of the system which would prevent us observing any reflection from the accretion disc.

For the sake of clarity, we show in Figure 2 only the EPIC PN spectrum in full, together with the three temperature thermal plasma model and the residuals. We also show in figure 2 the EPIC PN and MOS1 spectra around 6.7keV. Table 1 lists the best fit parameters. The need for a multi-temperature model is consistent with the RGS spectrum which showed emission from plasma with a range of temperatures. It is physically more plausible that the source will show a range in temperatures rather than several distinct temperatures.

Horne et al (1994) found evidence for a warm 'curtain' of material in OY Car using UV observations. We therefore investigated if our X-ray spectra could be better modelled using an absorber more complex than a neutral absorber. (In this study we only consider the EPIC PN data because of software problems in fitting all three EPIC spectra with complex absorbers). In fitting just the EPIC PN spectrum, we found that a two temperature MEKAL model with neutral absorption gave as good fits as a three temperature MEKAL model (χ^2_ν=1.71, 476 d.o.f). Fixing the column density of the neutral absorber to be $N_H = 3 \times 10^{19}$ cm^{-2}(Mauche & Raymond 2000) and letting the column density of a warm absorber (of the sort described by Cropper, Ramsay & Wu 1998) vary, we obtain χ^2_ν=1.61 (475 d.o.f) with temperatures kT=1.2 & 6.0keV and a warm absorber of $N_H = 1.3 \times 10^{21}$ cm^{-2}. This model is significantly (> 99.99 per cent using the F-test) better than the model which assumed only neutral absorption. Adding a third MEKAL model gave a fit (χ^2_ν=1.59, 473 d.o.f) which is better than a two temperature model at the 97.7 per cent level. We also used a partial covering model instead of a warm absorber. Using a two-temperature model gives a fit of χ^2_ν=1.63 (475 d.o.f). A three temperature model gave a significantly better fit (χ^2_ν=1.54, 473 d.o.f) with temperatures (kT=0.7, 2.5, 7.2keV) and a partial covering model of column $N_H = 6.3 \times 10^{21}$ cm^{-2}with a covering fraction of 0.51.

We conclude that there is evidence for complex absorption in the X-ray spectrum of OY Car. It is possible that this complexity is due to the fact that we have used the integrated spectrum: Ramsay et al (2001) found evidence
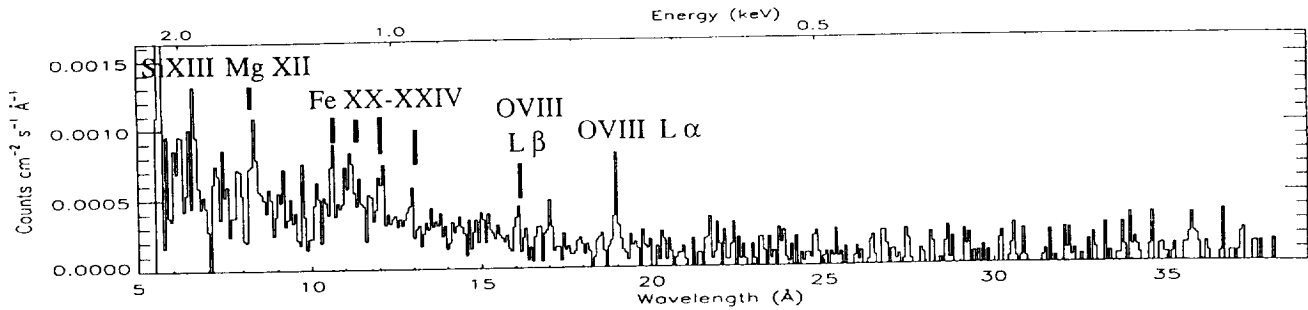
Fig. 1. The background subtracted RGS spectrum taken on 29 June 2000. The exposure was 55 ksec and includes both RGS1 and RGS2 data.
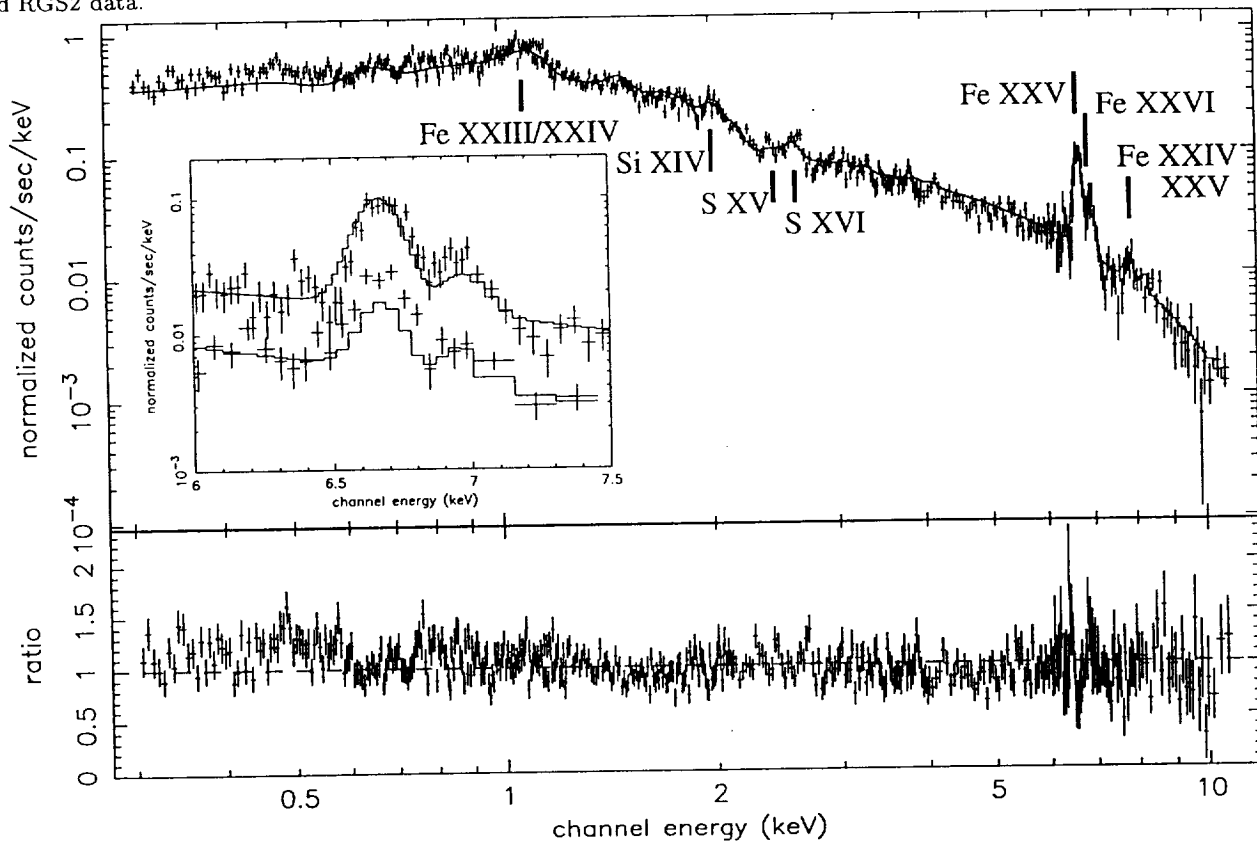

Fig. 2. Top panel: The integrated EPIC PN spectrum together with the best fit model using a neutral absorber and a three temperature thermal plasma model. Bottom panel: a plot of the data/model ratio. The inset shows the EPIC PN and MOS1 spectra with the best model fit covering 6.0–7.5keV.

for a spectral variation in the light curves. Alternatively, the absorbing column may vary over the orbital period or the 2242 sec period reported in Ramsay et al (2001). It is left to a future paper to investigate this.

4.3. Line studies

We can also determine the temperature structure of the plasma by measuring the intensity ratio of the H and He like line emission. Using the EPIC PN spectrum we can determine this ratio for Fe and S. We fitted a thermal bremsstrahlung emission component and added Gaussian

components to fit the He and H like emission lines. For Fe at 6.70 and 6.95keV we find a H/He like intensity ratio of $0.31^{+0.11}_{-0.08}$ and for S at 2.43 and 2.65 keV we find a ratio of $1.15^{+0.87}_{-0.06}$. Using the MEKAL thermal plasma model in XSPEC we obtained the H/He like intensity ratio verses ionisation temperature for the metal abundance derived in the fit (table 1) and plot this in figure 3. We find these ratios give temperatures of 6–8keV for Iron Kα and 2–3keV for Sulphur. Thus, as in our fits using multi-temperature MEKAL models, we need a range of temperatures to model the data. Indeed the temperatures derived from the line
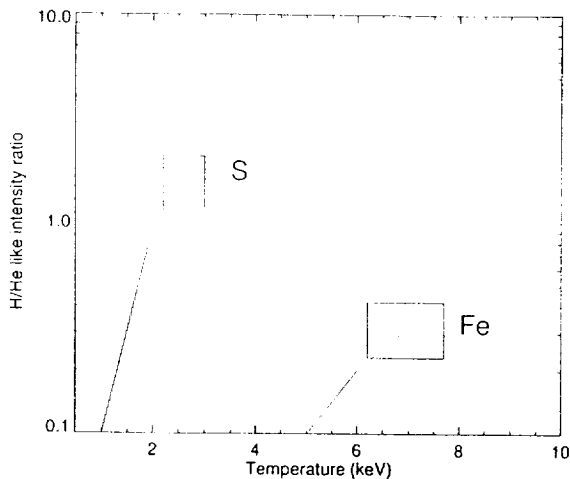
Fig. 3. The H/He like intensity ratio for Sulphur and Iron $K\alpha$ as a function of temperature. We plot the observed range determined using the EPIC PN spectrum.

N_H (cm^{-2})	$4.8^{+0.5}_{-0.4} \times 10^{21}$
Temperature (keV)	$7.7^{+0.5}_{-0.4}$, $3.3^{+0.2}_{-0.3}$, $0.76^{+0.04}_{-0.02}$
Metal abundance (solar)	$1.31^{+0.06}_{-0.08}$
Flux 0.2–10keV (ergs s^{-1} cm^{-2})	$4.0 \pm 0.6 \times 10^{-12}$
Bolometric flux (ergs s^{-1} cm^{-2})	$5.0 \pm 1.0 \times 10^{-12}$

Table 1. The best fit parameters for a simultaneous fit to all 3 integrated EPIC spectra using a 3 temperature MEKAL thermal plasma model.

fits are consistent with the temperatures of the hotter two thermal plasma components.

4.4. Are the lines broadened?

To determine whether the Fe 6.70keV and 6.95keV lines are broadened compared to that expected from pure thermal lines, we simulated a spectrum using the best-fit multi-temperature model tabulated in table 1, together with the same EPIC PN response as used in the fits and the same effective exposure (47ksec). We then fitted the observed EPIC PN spectrum between 4–6 and 9–11keV with a thermal bremsstrahlung component which was then fixed. We then included the energy range between 6–9keV and added two Gaussians to model the Fe lines at 6.70 and 6.95keV. We determined the width of the Gaussians and found that the observed widths (σ <30eV at 6.7keV, σ <60eV at 6.95keV) are consistent with the widths of the simulated thermal spectra. We conclude that the Fe lines are not significantly broadened and originate from a region optically thin to resonant scattering (Hellier, Mukai & Osborne 1998). The detection of the Kβ line (Figure 2) is consistent with the emission region having a low optical depth (Pozdnyakov, Sobol & Syunyaev 1983).

4.5. The luminosity

The flux values shown in Table 1 are the mean values determined from each EPIC spectrum. For a distance of 82±12 pc (Wood et al 1989) we determine the bolometric X-ray luminosity to be $6.0\pm0.8 \times 10^{30}$ ergs s^{-1}. This luminosity is similar to that reported for other non-magnetic CVs in quiescence: Pratt et al (1999) found $L_{X,bol} \sim 10^{30}$ ergs s^{-1}for OY Car using *ROSAT* data. We can determine the accretion rate, $\dot{M}$, from $L_{acc} = GM_1\dot{M}/R_1$, where L_{acc} is the accretion luminosity and $L_{bl} = L_{acc}/8$ (Popham & Narayan 1995), where L_{bl} is the boundary layer luminosity. For a white dwarf mass of 1.0 $M_\odot$(Ramsay et al 2001) and assuming the X-ray flux originates mainly from the boundary layer, we find a mass accretion rate during quiescence of 2.3×10^{14} g s^{-1} or 3.4×10^{-12} $M_\odot$yr^{-1}.

5. Summary

We have examined the X-ray spectra of OY Car obtained using *XMM-Newton*. These spectra have a much higher signal to noise and spectral resolution than previous X-ray spectra of dwarf nova. We find strong emission lines of various ionisation species. In fitting the EPIC spectra we require a multi-temperature plasma. This is confirmed by the line species seen in the RGS spectrum and also from the H/He-like intensity ratios of Iron and Sulphur. Adding a more complex absorber such as a warm absorber or a partial covering model to a neutral absorber significantly improves the fit to the data.

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