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ASTRONOMY AND ASTROPHYSICS

First *XMM-Newton* observations of a Cataclysmic Variable II: the X-ray spectrum 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 Kα emission with weaker iron Kβ 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 observation (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) (den Herder et al 2001) increased significantly towards the end of the observation: the high background data were therefore removed from the analysis. Before extracting spectra of OY Car, the 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 ($\sim 0.05 \mathrm{ct\,s^{-1}}$) we were able to extract the RGS spectrum using data from both RGS1 and RGS2 (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.

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Given the statistical quality of the RGS data we are unable to perform detailed spectral analysis. We can, however, use the iron line detections to roughly constrain the temperature of the plasma assuming that it is in collisional equilibrium. The detection of Fe XX lines requires a plasma temperature between 0.5 and 1.2 keV. However, the lack of emission from lower charge-states suggests that the temperature is actually higher than $\sim$0.8 keV. The simultaneous detection of Fe XXIV lines requires an additional temperature component, since these lines become prominent at temperatures larger than $\sim$1.3 keV. The lack of observable emission from the O VII He-like series but the detection of strong O VIII lines, puts a lower-limit of $\sim$0.4 keV on the oxygen emitting regions. The RGS spectrum suggests emission from a distribution of temperatures.

4. The EPIC spectra

4.1. General features

Spectra were extracted from all 3 EPIC cameras using apertures $\sim 30''$ in radius centered on OY Car, chosen so that the aperture did not cover more than one CCD. This encompasses $\sim$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 $\sim$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 extracted only 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 $\sim$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 found 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

The X-ray satellite *ASCA* (0.6–10keV) combined good spectral resolution together with reasonably large effective area. Around 15 dwarf novae were observed using *ASCA*. Amongst the brightest 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 the integrated spectra from the three EPIC cameras simultaneously using models of increasing complexity.

A single temperature thermal plasma model with a model for absorption by neutral gas (the `MEKAL` and `WABS` models in `XSPEC`) gave a fit with χ^2_ν=2.23 (890 d.o.f.) and a best fit temperature of kT=6.1keV. Adding a second thermal plasma model yielded 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 held 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) and is due to fluorescence either from the surface of the white dwarf or surrounding local material. By adding a Gaussian (fixed at 6.4keV) to the model described above, we derive an upper limit on the equivalent width of 24eV for a line of width 100eV and 29eV for a line of width 50eV. The fact that we did not detect a fluorescent line is possibly due to the high inclination of the system which may 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 more than one temperature.

In their observations of SS Cyg in quiescence Done & Osborne (1997) found evidence that the absorption component is more complex than a simple neutral absorber. We therefore investigated if our X-ray spectra could be better modelled using a complex absorber. (In this study we only consider the EPIC PN data because of software problems in fitting all three EPIC spectra with complex absorbers). When we fitted the EPIC PN spectrum alone 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): a third temperature component is not necessary. Using a warm absorber (of the sort described by Cropper, Ramsay & Wu 1998) vary and fixing the column density of the neutral absorber to be $N_{\rm H} = 3\times10^{19}$ cm^{-2}(Mauche & Raymond 2000) we obtain χ^2_ν=1.61 (475 d.o.f) with temperatures kT=1.2 & 6.0keV and a warm absorber of temperature T$\sim 5\times10^5$ K and column density $N_{\rm H} = 1.3\times10^{21}$ cm^{-2}. The implied value for the ionisation parameter is $\xi = 0.058, (= L/nr^2$ where L is the luminosity, n the density and r the distance of the absorber from the irradiating source). The addition of the warm absorber produces significant absorption edges near

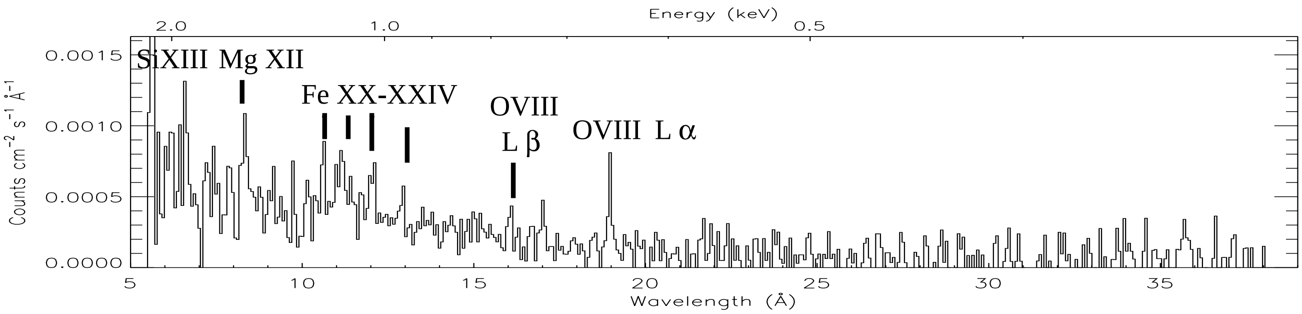

Fig. 1. The background subtracted RGS spectrum taken on 29 June 2000. The exposure was 55 ksec and includes both RGS1 and RGS2 data.

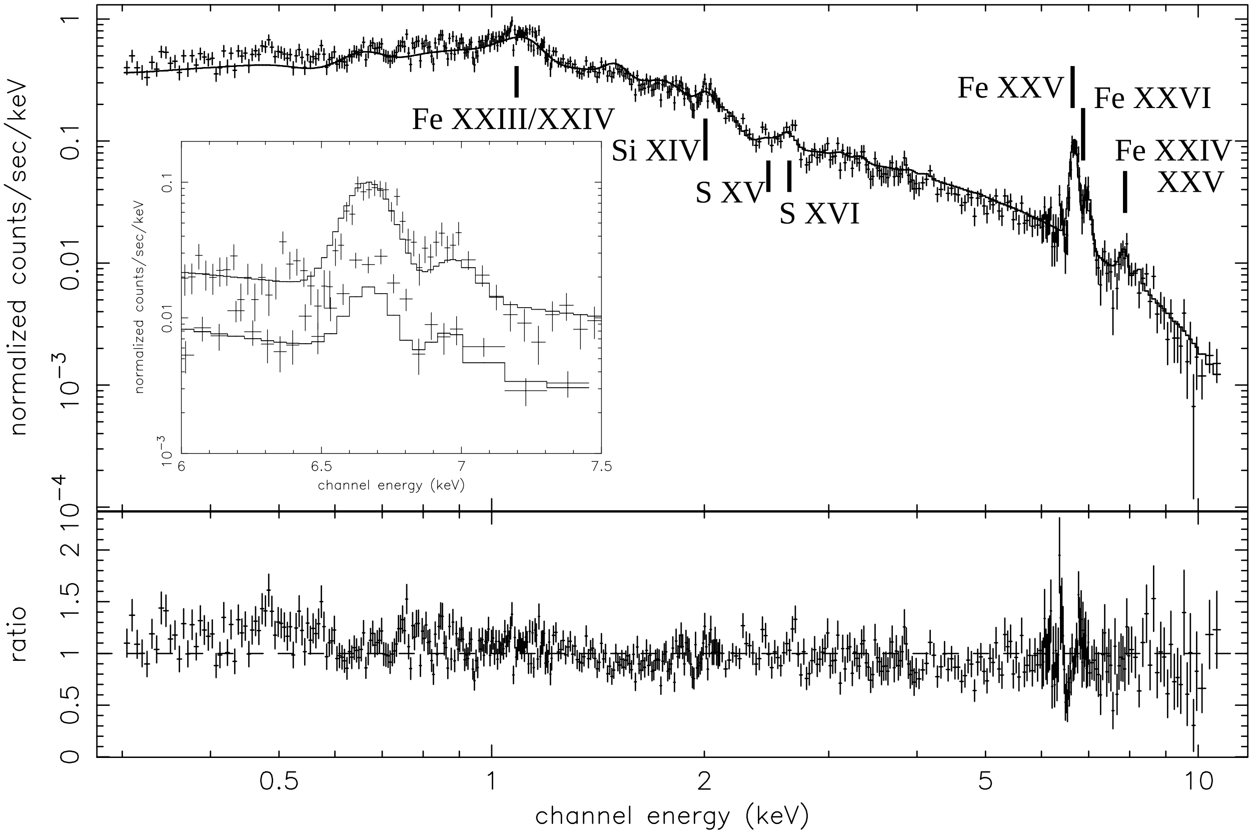

Fig. 2. Top panel: The integrated EPIC PN spectrum together with the best fit model using a neutral absorber and a three temperature thermal plasma model. Bottom panel: a plot of the data/model ratio. The inset shows the EPIC PN and MOS1 spectra with the best model fit covering 6.0–7.5keV.

$\sim$0.6keV. The signal to noise of the RGS spectra is too low to detect these edges. This warm absorber model is significantly ($>$ 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 $N_{\rm H} = 6.3 \times 10^{21}$ 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. We caution, however, that we have used the integrated spectrum in our study: Ramsay et al (2001) found evidence for a spectral variation in the light curves. It is left to a future paper to investigate this.

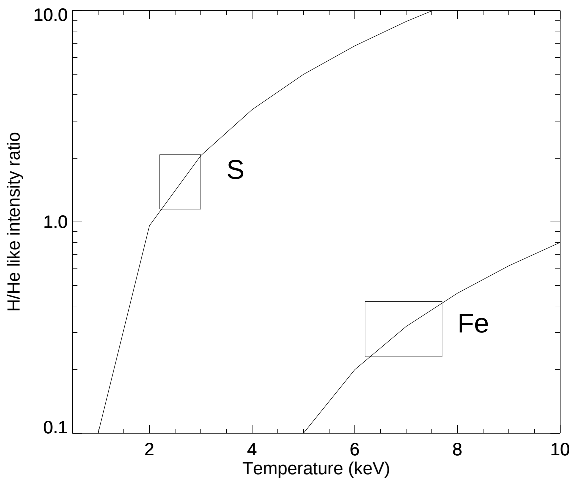

Fig. 3. The H/He like intensity ratio for sulphur and iron Kα as a function of temperature. We plot the observed range determined using the EPIC PN spectrum.

$N_{\rm H}$ (cm^{-2})	$4.8^{+0.5}_{-0.4}\times10^{21}$
Temperature (keV)	$7.7^{+0.5}_{-0.4}$, $3.3^{+0.2}_{-0.3}$, $0.76^{+0.04}_{-0.02}$
Metal abundance (solar)	$1.31^{+0.06}_{-0.08}$
Observed flux 0.2–10keV (ergs s^{-1} cm^{-2})	$4.0\pm0.6\times10^{-12}$
Bolometric flux (ergs s^{-1} cm^{-2})	$5.0\pm1.0\times10^{-12}$

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

4.3. Line studies

We can also determine the temperature 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 fits are consistent with the temperatures of the hotter two thermal plasma components.

4.4. 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 $4.0\pm0.8\times10^{30}$ ergs s^{-1}. This luminosity is similar to that reported for other non-magnetic CVs in quiescence: Pratt et al (1999) found $L_{\rm X,bol}\sim10^{30}$ ergs s^{-1}for OY Car using *ROSAT* data. The luminosity in the *ROSAT* energy band (0.1–2keV) is 1.9×10^{30} ergs s^{-1}. We can determine the accretion rate, $\dot{M}$, from $L_{\rm acc}=GM_1\dot{M}/R_1$, where $L_{\rm acc}$ is the accretion luminosity and $L_{\rm bl}=L_{\rm acc}/8$ (Popham & Narayan 1995), where $L_{\rm bl}$ 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 1.3×10^{14} g s^{-1} or 1.9×10^{-12} $M_\odot$yr^{-1}. The true luminosity and accretion rate maybe significantly higher since van Teeseling, Beuermann & Verbunt (1996) showed that the observed flux is anti-correlated with inclination: for high inclination systems most of the flux is absorbed by the accretion disc.

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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