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Three Polars and a Dwarf Nova: Multiwavelength Studies of Eclipsing Cataclysmic Variable Stars with XMM-Newton

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Abstract. XMM-Newton has a number of capabilities that make it uniquely suited to furthering our understanding of cataclysmic variable stars. It has a large collecting area, ideal for obtaining high signal-to-noise spectra and light curves of these modestly faint objects over a wide bandpass. The observatory can view X-ray, UV, and optical light simultaneously, allowing correlated variability studies to be made. The satellite's high Earth orbit means that close binary star systems can be viewed for long periods of time over several orbital cycles, uninterrupted by Earth occultations. XMM-Newton observations of eclipsing CVs are providing us with high signal-to-noise light curves and spectroscopy over a large range in wavelength, which allow us to study the physics and geometry of accretion under different conditions of gravity and magnetic field strength. With XMM-Newton we can search for oscillations and, for polars, measure changes in the orbital period and accretion spot longitude; this gives us additional information about the accretion process. This paper reports on analysis of XMM-Newton observations of four CVs: the polars DP Leo, WW Hor, and UZ For, and the dwarf nova OY Car. All of them are eclipsing and have binary orbital periods less than 130 minutes.

1. Introduction

This book, like the conference that preceded it, celebrates the broad and prolific contributions of astronomer Jan van Paradijs. His passion was to fathom the universe of compact stars that lived long, ordinary lives but were going out in a riot of bursts and cataclysms. Like the objects he studied, he was highly energetic, always in motion. His publications, totaling many hundreds, survive him and enrich our work.

Among the binary star systems studied by van Paradijs were the cataclysmic variables, which are distinguished by the presence of a white dwarf that accretes matter from a nearby lower main sequence star. If the white dwarf has a sufficiently strong magnetic field (of order 10^7 G) matter from the donor star will be threaded onto field lines and fall radially onto the white dwarf. These objects are called polars. For close binaries in which the white dwarf has only a weak magnetic field, matter from the Roche lobe filling donor star forms a rotating disk around the white dwarf. If the viscosity in the disk is low, matter is temporarily stored in the disk and the accretion onto the white dwarf will be episodic, with a time scale of weeks or months. Such a release of potential gravitational energy results in a brightening in light and the objects are called dwarf novae. The first such flaring star was discovered in 1855.

This short contribution summarizes early observations of cataclysmic variables made with XMM-Newton (hereafter, XMM), launched on December 10, 1999. XMM, built principally for high-throughput X-ray spectroscopy, comprises three types of instruments: three X-ray-sensitive European Photon-counting Imaging Cameras (EPIC), two Reflection Grating Spectrometers (RGS), and an optical/ultraviolet telescope (OM) with several filters. A complete description of the satellite observatory and its instruments can be found in Jansen et al. (2001), den Herder et al. (2001), Strüder et al. (2001), Turner et al. (2001), and Mason et al. (2001).

It is especially appropriate that we honor the memory of van Paradijs with a contribution using data from XMM because this is the first mission that combines both multiwavelength capability (X-ray, UV, and optical) with the ability to make long observations (because of the 48 hour orbital period of XMM). Thus many binary orbits of the short-period cataclysmic variables, which are typically a few hours or less, can be observed without interruption from Earth occultations. These observing features realized a long-held dream of many astronomers, including van Paradijs.

The cataclysmic variables we report on comprise four eclipsing systems: three polars – DP Leo, WW Hor, and UZ For – and a dwarf nova, OY Car. At the time of the publication of this book, analyses of these observations will have been published in peer-reviewed journals. Thus we give here only a summary of our findings, with a reference to the published papers.

2. DP Leo

DP Leo, which has an orbital period of 89.9 min, was the first known eclipsing polar. Shortly after its serendipitous discovery with the Einstein X-ray observatory, it was confirmed as a magnetic CV on the basis of its strongly modulated polarized emission in the optical. From later observations, Bailey et al. (1993) found that the longitude of the accretion spot is slowly changing, suggesting that the white dwarf is not rotating perfectly synchronous with the orbital period. Our observation of DP Leo with XMM in the year 2000, when combined with observations from the past 20 years, confirmed that the accretion spot longitude is changing linearly with time by $2^\circ\mathrm{yr}^{-1}$ (Fig. 2). Apparently, the spin period of the white dwarf is shorter than the orbital period by $10^{-6}\mathrm{s\ s}^{-1}$. From our analysis of the eclipse ephemeris, we found clear evidence that the orbital period of DP Leo is decreasing (Fig. 2). The time-scale for this decrease is $\sim 3 \times 10^7\mathrm{yr}$, one order of magnitude faster than expected for energy loss by gravitational radiation alone.

During the XMM observation DP Leo was in an intermediate accretion state (peak magnitude $R \sim 17.5$). In the X-ray spectrum, we observed previously undetected hard X-ray emission due to bremsstrahlung from the shock-heated gas in the accretion column. Below 0.3 keV the spectrum is dominated by blackbody radiation ($\sim 25-30$ eV) from the heated photosphere near the accretion region.

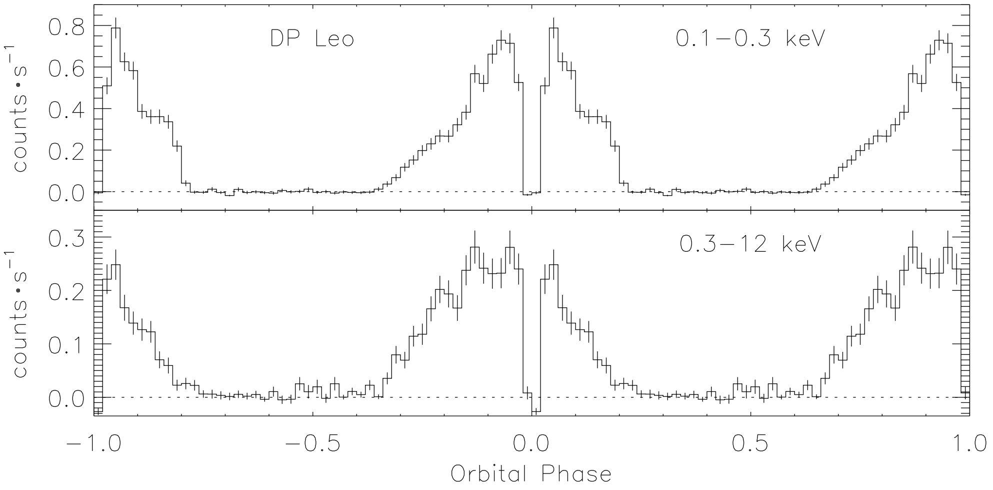


Figure 1. X-ray light curve of DP Leo folded on the 89.8-min orbital period. Shown are the combined count rates of all three EPIC detectors. The particular choice for the two energy ranges almost completely separates the blackbody component (upper panel) from the bremsstrahlung component (lower panel).

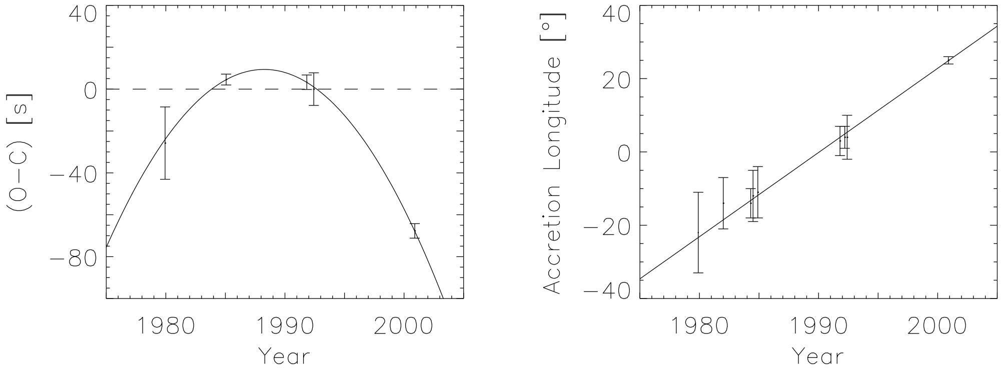


Figure 2. Eclipse timing and accretion longitude changes in DP Leo. The left panel shows the deviation of the observed eclipse timing from that predicted by a linear ephemeris (dashed line) from earlier observations. A quadratic ephemeris (solid line) is required to fit the data point obtained with XMM in December 2000. The right panel shows how the longitude of the accretion spot has been increasing with time.

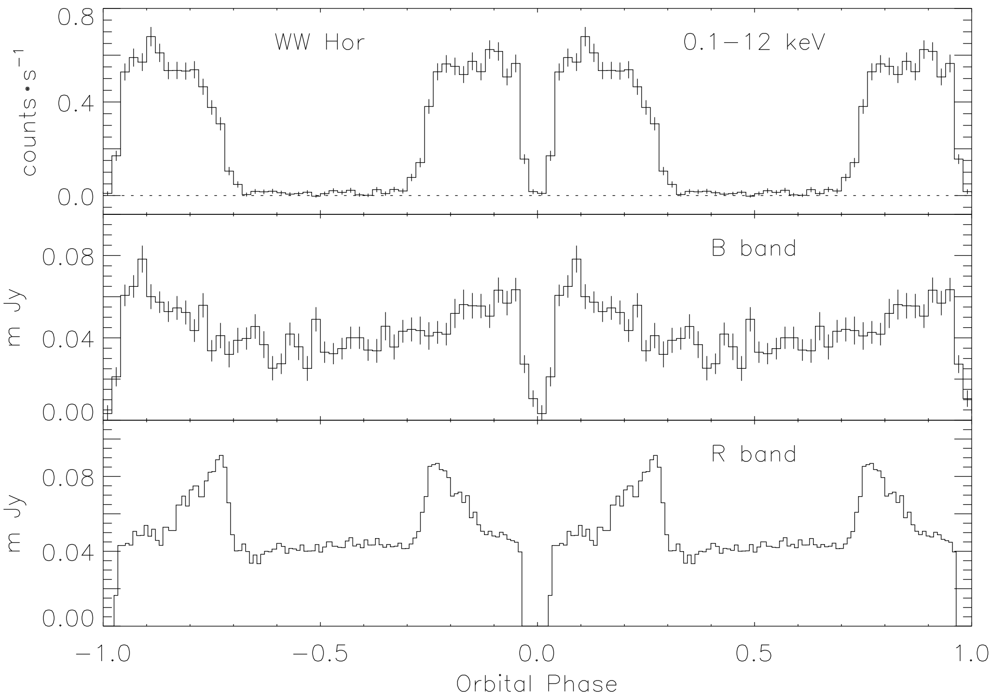


Figure 3. X-ray and optical light curves of WW Hor folded on the 115.5-min orbital period. The upper panel shows the X-ray flux, which is solely due to bremsstrahlung from the optically thin post-shock region. The B-band light curve (middle panel) was obtained with the XMM-Newton Optical Monitor. Its modulation is due to blackbody radiation from the heated pole cap of the white dwarf. The R-band light curve, obtained with a ground-based telescope, shows the double-peaked profile typical for cyclotron radiation from the accretion region.

Using a multi-temperature model of the post-shock flow, we estimated that the white dwarf has a mass of 1.4 $M_\odot$ and that the unabsorbed X-ray luminosity (soft and hard component) is $\sim 4 \times 10^{31}$ erg s^{-1}.

In DP Leo, the hard X-ray light curve does not have the expected top-hat shape for optically thin bremsstrahlung from the post-shock region (cf. X-ray light curve of WW Hor in Fig. 3). The observed cosine shape is characteristic for an optically thick emission region. The soft X-ray light curve of the blackbody component has an irregular and asymmetric shape, suggesting a complex accretion geometry. Flaring in the light curve appears to be concentrated around the eclipse. This might be due to an additional accretion region that is slightly offset in latitude and longitude from the main region. The details of our analysis of the XMM data are discussed in Ramsay et al.(2001b) and Pandel et al. (2002).

3. WW Hor

WW Hor was discovered serendipitously with the EXOSAT observatory. The polar has an orbital period of 115.5 min. As for DP Leo, Bailey et al. (1993) found for WW Hor significant variations of the accretion spot longitude. Our analysis of the XMM data showed that these variations are not due to a slightly asynchronous rotation of the white dwarf, but rather that the longitude is correlated with the accretion rate.

During the XMM observation, WW Hor was in an intermediate accretion state with optical peak magnitudes of $B \sim 19.6$ and $R \sim 18.8$. In the X-ray spectrum, we only detected the hard emission that is due to bremsstrahlung from the post-shock region. This is in contrast to previous ROSAT observations that also found a soft blackbody component. It is possible that, during the XMM observation, accretion was occurring over a larger area. This would lead to a reduced local heating rate and hence a lower temperature of the soft X-ray component. Using a multi-temperature model for the post-shock flow, we determined a white dwarf mass of ~ 1.1 $M_\odot$ and an unabsorbed X-ray luminosity in the hard component of $\sim 2 \times 10^{31}$ erg s^{-1}.

The X-ray light curve of WW Hor (Fig. 3) exhibits the top-hat shape that is expected for optically thin bremsstrahlung from the accretion region. For WW Hor we obtained simultaneous B band data from the Optical Monitor, as well as R band data from a ground-based telescope. The orbital modulation in the B-band light curve (Fig. 3) is due to blackbody radiation from an extended region of the white dwarf's photosphere that is heated by accretion. Cyclotron radiation from the accretion column caused the double-peaked profile in the R-band light curve. The X-ray and optical light curves allowed us to directly measure the horizontal and vertical temperature variations in the accretion column. We found that the cyclotron radiation originates from a larger height (~ 0.01 white dwarf radii) than the X-rays. Also, soft X-rays are emitted closer to the surface than hard X-rays. These findings are consistent with the general picture that the shock-heated gas cools and compresses as it settles on to the white dwarf. The soft X-ray emitting region has a horizontal extent of $\sim 40°$, whereas the hard X-ray and cyclotron emitting regions are much smaller. This result indicates that the temperature of the post-shock region is increasing toward the center. Detailed results of our analysis are presented in Ramsay et al.(2001b) and Pandel et al. (2002).

4. UZ For

With an orbital period of 126.5 minutes, the eclipsing polar UZ For is within the sparsely populated 2–3 hour "period gap" of CVs. During an XMM observation on 14 January 2001, UZ For was found in a peculiar state, exhibiting extremely low X-ray luminosity and occasional X-ray and UV flaring (Fig. 4). For most of the 20 ks exposure with the EPIC cameras, UZ For was only barely detected and ~ 800 times fainter than during the high state observed previously with the ROSAT satellite. The likely origin of the weak X-ray emission is bremsstrahlung from the main accretion region. The UV flux detected with the Optical Monitor is consistent with 11000-K blackbody radiation from the photosphere of the

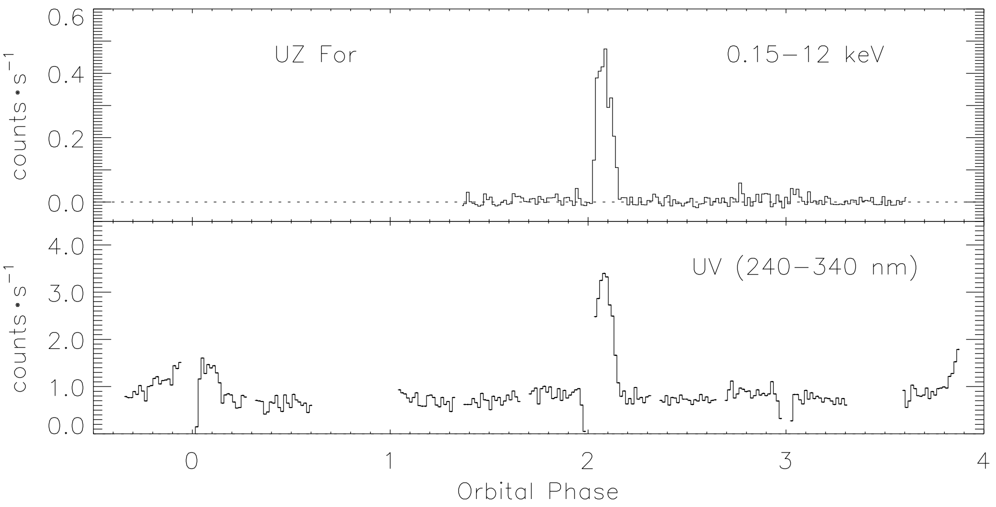
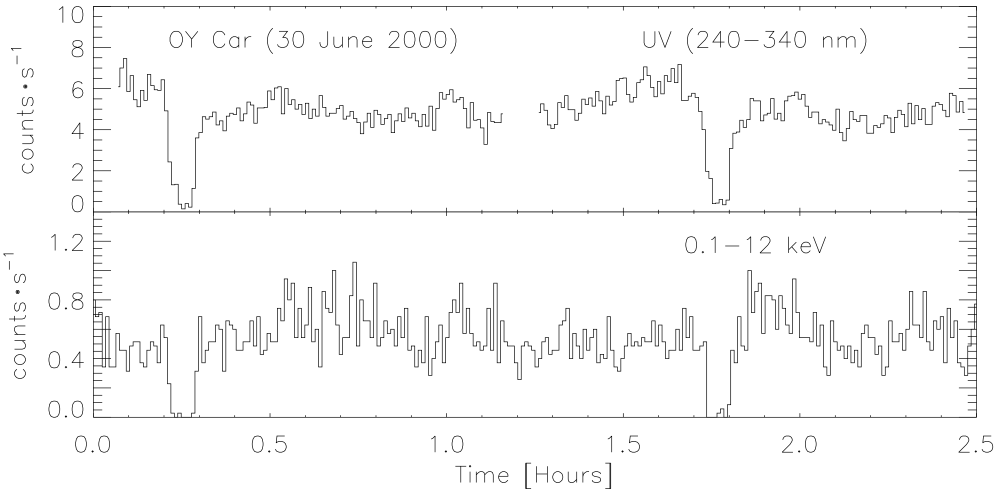


Figure 4. X-ray and UV light curves of UZ For during a very low state of accretion. Shown are the combined X-ray count rates of the three EPIC detectors (upper panel) and the count rates measured by the XMM-Newton Optical Monitor using the UVW1 filter (lower panel). The X-ray/UV flare near orbital phase 2 was caused by an intermittent increase of the mass transfer rate from the secondary to the white dwarf.

white dwarf. The light curve shows a small orbital modulation, which is likely due to a large, heated pole cap. Most striking about the XMM observation of UZ For was the simultaneous X-ray and UV detection of a large-amplitude transient event that lasted $\sim$ 900 s. This event was likely caused by accretion of $10^{17} - 10^{18}$ g of gas on to the white dwarf. The X-ray spectrum of the transient is consistent with $\sim$ 6 keV thermal bremsstrahlung from the post-shock region, but it does not show the typical blackbody component from reprocessing of hard X-rays in the atmosphere of the white dwarf. Cyclotron radiation from the same region probably caused the increase of the UV flux. Two more transient events were detected by the Optical Monitor while the EPIC cameras were not operating. After examining various hypotheses, we concluded that the unusual flaring behavior during the low state of UZ For was probably caused by intermittent increases of the mass transfer rate due to stellar activity on the secondary. A more detailed discussion of our results can be found in Pandel & Córdova (2002).

5. OY Car

OY Car is the only non-polar in this sample of four CVs. It is an eclipsing dwarf nova with an orbital period of 91 minutes. XMM observed OY Car ($V \sim 16$) twice during the first year of the mission: 29–30 June 2000 (four days after a short outburst of the dwarf nova) and 7 August 2000 (with no intervening outbursts). Simultaneous X-ray and optical/UV light curves are shown in Fig.



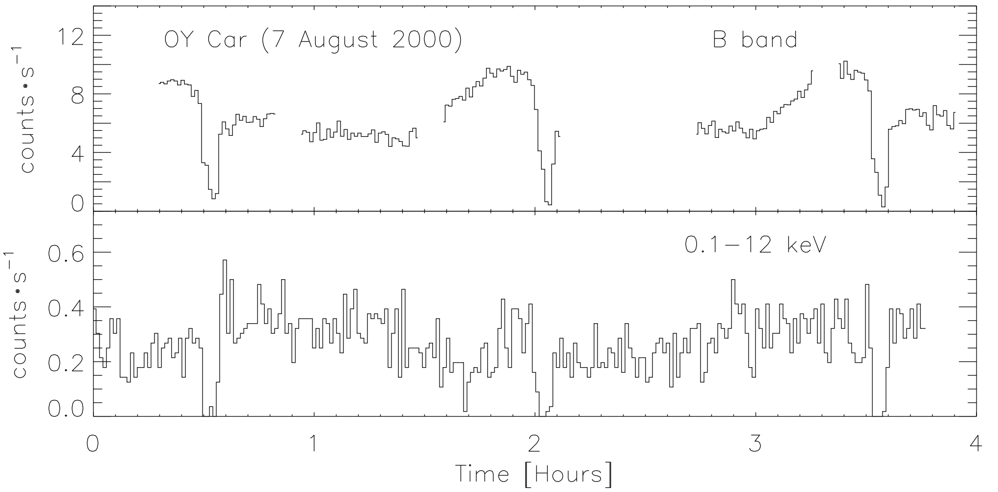


Figure 5. X-ray and UV light curves of OY Car for two different epochs. Shown are the combined X-ray count rates of the two EPIC MOS detectors and the count rates measured by the XMM-Newton Optical Monitor using the B filter and the UVW1 filter, respectively. The dips in the light curves are the eclipses of the white dwarf by the secondary.

5. The spectrum of OY Car from the first observation (which, at 50 ks, was much longer than the second observation) shows strong Iron K alpha emission with weaker Iron K beta emission, and also Silicon and Sulphur lines. The spectra are best fitted with a three temperature plasma model with a partial covering absorber. A multiple temperature emission spectrum is confirmed with simultaneous RGS observations. For a distance of $\sim$ 82 pc we determine a bolometric X-ray luminosity of 4×10^{30} erg s^{-1}. For a white dwarf mass of 1 $\mathrm{M}_\odot$ and assuming the X-ray flux comes from the boundary layer, we find a mass accretion rate of 1.3×10^{14} g s^{-1}, or 1.9×10^{-12} $\mathrm{M}_\odot$ yr^{-1}. However, we note that for this high inclination system much of the flux may be absorbed by the disk in our line of sight and hence the true luminosity and accretion rate may be higher.

We found in the X-ray light curve of OY Car a quasi-stable modulation at $\sim$ 2240 s, which is most prominent at the lowest energies. We speculate that this may be related to the spin period of the white dwarf. The duration of the eclipse ingress and egress in X-rays is 20–30 s. This indicates that the bulk of the X-ray emission originates from the boundary layer which has a negligible height above the surface of the white dwarf. The eclipse profile implies a mass of $M_1 = 0.9 - 1.1$ $\mathrm{M}_\odot$ for the white dwarf and $M_2 = 0.08 - 0.11$ $\mathrm{M}_\odot$ for the secondary star. A detailed description of our analysis can be found in Ramsay et al. (2001a) and Ramsay et al. (2001c).

6. Summary

The immensely diverse scientific bounty that a study of these fascinating systems can produce is summarized in Warner (2000). With detailed multiwavelength studies afforded by XMM's capabilities, observers can hope to address many long-standing questions concerning such binary stars, among them: What is the cause and nature of their behavior as they go into and emerge from the period gap? Through what mechanism do CVs evolve toward shorter orbital periods? What is the cause of both high and low states in polars, and the origin of their flares during low states? What is the physics of the transfer of matter from the donor star? What are the physical conditions in the X-ray emitting regions for the various subclasses of CVs? What is the geometry of these regions? For the dwarf novae, what is the influence of the high-energy emission on the disk emission and structure? What is the origin of the soft X-ray excess in polars? How does the magnetic field affect accretion? As this short paper illustrates, XMM observations promise new insights into the rich spectrum of physical phenomena exhibited by CVs.

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