Correlated X-ray and optical variability in intermediate polars during their outbursts

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Abstract. We present a study of the evolution of the optical and X-ray fluxes during outbursts of two short-period cataclysmic variables, the confirmed intermediate polar CC Scl and the intermediate polar candidate FS Aur. We found that the X-ray and optical light curves are well correlated in both objects, although the amplitudes of outbursts in X-rays are smaller than those in the optical. The ratio of the outburst amplitudes in X-rays and the optical in both objects is close to \( \sim 0.6 \). This is significantly higher than was observed during the outburst of the non-magnetic dwarf nova U Gem, in which this ratio was only \( \sim 0.03 \). The obtained data also suggest that the dependence between the X-ray and optical fluxes must steepen significantly toward very low accretion rates and very low fluxes. Similarities in the behaviour of CC Scl and FS Aur indicate strongly the magnetic nature of the white dwarf in FS Aur.

1. Introduction

Cataclysmic Variables (CVs – for a comprehensive review, see Warner 1995) are close interacting binary systems in which a white dwarf (WD) accretes material from its late-type low mass companion. In the absence of a strong magnetic field, the material transferred from the donor star forms an accretion disc around the WD and gradually spirals down onto its surface. If the mass-transfer rate is low, the accretion disc can suffer a thermal instability caused by hydrogen ionisation, resulting in outbursts. Dwarf novae (DN) are an important subset of CVs, which undergo such outbursts. Intermediate polars (IP) are another subset of CVs in which the magnetic field of the WD is strong enough to disrupt the inner accretion disc and force the accreting material to flow along field lines on to one or both magnetic poles. Outbursts can also arise in the truncated discs of IPs, although only a few such objects are known (e.g., YY Dra, CC Scl, GK Per).

The difference in the strength of the magnetic field of the WD in non-magnetic DNe and IPs determines the time evolution of the X-ray radiation during their outbursts.
The X-ray emission of non-magnetic CVs is believed to originate from regions very close to the WD surface, most likely in a boundary layer. During an outburst, the boundary layer transitions from optically thin to optically thick, which may lead to a suppression of the X-ray flux. Indeed, only a very few non-magnetic DNe are known in which the X-ray flux increases during an outburst (e.g., U Gem – Mattei et al. 2000). In IPs the accretion occurs onto the magnetic poles of the WD, and the boundary layer does not exist. Thus the X-ray flux during an IP outburst is expected to increase. Indeed, such a behaviour was observed in the above-mentioned outbursting IPs (Szkody et al. 2002; Woudt et al. 2012; Šimon 2015). Here we present a comparison of the evolution of the optical and X-ray fluxes during outbursts of two CVs with similar orbital periods, the confirmed IP CC Scl and the IP candidate FS Aur.

2. Background and the data

2.1. CC Sculptoris

CC Scl was discovered as the ROSAT source RX J2315.5–3049 (Voges et al. 1999) and later classified as a dwarf nova (Schwope et al. 2000), although no outbursts have yet been detected. Ishioka et al. (2001) observed two outbursts of CC Scl, one of which appeared to be a superoutburst due to the detection of superhumps, thus classifying CC Scl as a SU UMa-type dwarf nova. From time-resolved spectroscopy, Chen et al. (2001) derived an orbital period of 84.1 min. In 2011, Woudt et al. (2012) performed optical spectroscopic, high-speed photometric and Swift X-ray observations of the superoutburst of the object. They detected WD spin modulations with a period of 6.49 min which are seen in both optical and X-ray light curves only during the outburst. Thus, CC Scl is a confirmed intermediate polar with one of the shortest orbital periods among IPs.

Figure 11 in Woudt et al. (2012) shows that an X-ray count-rate from CC Scl increased in the outburst. In order to compare the changes in the optical and X-ray energy ranges, we used the observations published in Woudt et al. (2012). We note that the X-ray spectrum of CC Scl has changed significantly during the outburst and the following decline, mostly because of changes in the absorption column (Woudt et al. 2012). For this reason, in our work we used unabsorbed X-ray fluxes in the energy band 0.3–10 keV. They were calculated using the partially-covered cooling flow model described in Woudt et al. (2012). These fluxes were not published in the paper, but were provided to us by K. L. Page, whose help is very much appreciated. We also used the V observations of F.-J. Hambusch which were published in Woudt et al. (2012) and stored in the AAVSO database. In addition, we extracted the 1-d averaged SAAO observations from figure 1 in their paper. The V magnitudes were then converted into fluxes and interpolated to the times of the X-ray observations.

2.2. FS Aurigae

FS Aur is a peculiar CV showing multiple periodic photometric and spectroscopic variabilities (Tovmassian et al. 2003, 2007). Its orbital period of 85.7 min is determined from the radial velocity variations of emission lines (Thorstensen et al. 1996; Neustroev 2002), and is close to that of CC Scl. The puzzling behaviour of FS Aur is explained within the frame of an enhanced IP scenario with a precessing, fast-rotating magnetically accreting WD (Tovmassian et al. 2007). The spin period of the WD is expected to
be of the order of 50–100 s. This hypothesis has received an observation confirmation after finding strong indications that many observed properties of FS Aur closely resemble those of other IPs (Neustroev et al. 2013). However, the coherent spin modulations are not yet discovered, thus the IP status of FS Aur is still unconfirmed.

FS Aur shows regular outbursts with a total duration of about 4 d and of relatively low amplitude of $\sim$2 mag, with recurrence time of 18.1±2.5 d (Neustroev et al. 2012). Most of the observed outbursts had very similar light curves. It is interesting that FS Aur also exhibits strong variability even in quiescence. For example, Neustroev et al. (2012) reported that during a 5-month observational campaign in 2010-2011 the average quiescent level of the system has increased by 0.3–0.4 mag. Sometimes FS Aur experiences drops in brightness by about 1.5 mag (Tovmassian et al. 2007). Chavez et al. (2012) showed that the optical brightness of FS Aur in quiescence varies within a wide range (17.4–15.2 mag) and these modulations of the light curve are possibly periodic with a $\sim$900-d period.

FS Aur is a rather hard and relatively bright X-ray source. Neustroev et al. (2013) reported the X-ray observations of FS Aur obtained with ROSAT, Chandra and Swift in quiescence at different optical brightness level. They noted that the X-ray flux varies proportionally to the optical flux. In order to study this effect in more detail, in this work we additionally use several new observations obtained recently with Suzaku (Neustroev & Tsygankov 2014) and Swift. Thus, our quiescence data cover about a 1-mag range of optical magnitudes.

In January 2015, we were lucky to catch FS Aur at the onset of a new outburst, the development of which we traced in detail from the maximum to quiescence. We obtained 11 nights of optical photometry using the 0.35 m Celestron C14 robotic telescope, located at New Mexico Skies in Mayhill, New Mexico. The data were taken with an SBIG ST-10XME CCD camera and the standard Johnson V filter. We were able to start our ToO Swift X-ray observations at the optical light maximum and we observed until the system returned back to quiescence. We note that an X-ray count-rate had also increased in the outburst, similarly to CC Scl. To calculate the X-ray fluxes in the energy band 0.3–10 keV, we used the three-temperature cooling flow model described in Neustroev et al. (2013).

![Figure 1](image_url)
Figure 2. The optical/X-ray flux diagram for CC Scl.

Figure 3. The optical/X-ray flux diagram for FS Aur in quiescence.
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Figure 4. The optical/X-ray flux diagram for FS Aur in quiescence (black diamonds) and in the outburst (blue triangles).

3. Results

Figure 1 shows the optical and X-ray light curves of the outbursts of CC Scl (left-hand panel) and FS Aur (right-hand panel), and in Figs. 2, 3 and 4 we show the optical/X-ray flux diagrams. The morphology of the optical and X-ray light curves of CC Scl is very similar, resulting in a nearly linear dependence between the X-ray and optical fluxes (Fig. 2). However, the outburst amplitude in the X-rays is less than in the optical. In order to characterize the difference in amplitudes of flux variations, we introduce a parameter \( R \), the rate of changes of the X-ray and optical fluxes:

\[
R = \frac{F_{x,\text{max}}}{F_{x,\text{min}}} / \frac{F_{\text{opt,\text{max}}}}{F_{\text{opt,\text{min}}}}
\]

where \( F \) are the maximal and minimal X-ray and optical fluxes. For CC Scl, \( R \approx 0.62 \). An interesting feature of the optical/X-ray flux diagram is that the fitted line crosses the zero optical flux axis with a non-zero X-ray flux. This indicates that the dependence between the X-ray and optical fluxes must steepen significantly toward very low accretion rates (and very low fluxes).

The optical and X-ray fluxes of FS Aur in quiescence show a similar dependence with \( R_{\text{qui}} \approx 0.71 \) (Fig. 3). The fitted line also crosses the zero optical flux axis with a non-zero, positive X-ray flux. During the outburst of FS Aur, the dependence between the X-ray and optical fluxes became less steep, though not very significantly (Fig. 4). The ratio of the outburst amplitudes in X-rays and the optical is \( R_{\text{outb}} \approx 0.47 \).

Thus, we obtained that during the outbursts of the confirmed IP CC Scl and the IP candidate FS Aur, their X-ray fluxes increased with a similar rate \( R \). This rate is signifi-
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cantly higher than was observed in those normal dwarf novae with a non-magnetic WD, which showed an increase of X-ray flux in outburst. For example, during an outburst of U Gem (Mattei et al. 2000) $R$ was only about 0.03.

4. Summary and Conclusion

We investigated the relation between the optical and X-ray fluxes during outbursts of two CVs with similar orbital periods. We found the following:

1. The ratio of the outburst amplitudes in X-rays and the optical in both objects is close to $\sim 0.6$, that is significantly larger than in the non-magnetic dwarf nova U Gem.

2. The dependence between the X-ray and optical fluxes must steepen significantly toward very low accretion rates and very low fluxes.

3. Similarities in the behaviour of CC Scl and FS Aur indicate strongly the magnetic nature of the WD in FS Aur.

Acknowledgments. VS thanks Deutsche Forschungsgemeinschaft (DFG) for financial support (grant WE 1312/48-1). This research has made use of data obtained from the Suzaku satellite, a collaborative mission between the space agencies of Japan (JAXA) and the USA (NASA). Our research was based on X-ray observations by NASA missions Chandra and Swift which we acknowledge. We thank Neil Gehrels for approving the Target of Opportunity observation with Swift and the Swift team for executing the observation. We acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research. We acknowledge the data kindly provided to us by our colleague K. L. Page.

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