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Cataclysmic variables and related objects with INTEGRAL†

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Abstract. We present selected results of observations and monitoring of cataclysmic variables (CVs) and related objects by the instruments IBIS and OMC onboard *INTEGRAL*. We analyse the behaviour of the intermediate polar (IP) V1223 Sgr in a state which we call a shallow low state. We present far X-ray spectra (E up to 60 keV), and the optical and far X-ray orbital modulation. The relation between far X-ray and optical flux appears to be stable over about 400 days. We also present far X-ray observations of some other CVs (or at least upper limits of their far X-ray fluxes) and show that the systems with magnetized white dwarf (like polars and IPs) are observable with *INTEGRAL*. The OMC light curves show that an outburst and a shallow low state of IX Vel are caused by the mass transfer variations, and not by the thermal instability of the disk, and that the amplitude of the flickering decreases with the decreasing intensity of the "stable" component.

Keywords. accretion, accretion disks, magnetic fields, binaries (including multiple): close, circumstellar matter, stars: dwarf novae, novae, cataclysmic variables, X-rays: binaries.

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1. Introduction

Cataclysmic variables (CVs) are close binary systems in which mass accretion onto a white dwarf (WD) occurs. The observed X-ray and optical activity, luminosity and spectrum of CVs crucially depend on the mass accretion rate $\dot{m}$ and the strength of the magnetic field (MF) of the WD. This strength generally increases from non-magnetic CVs through intermediate polars (IPs) to polars. Bremsstrahlung is the dominant process for the X-ray radiation of CVs (see Warner (1995) for a review). The temperature (kT) of the X-ray spectrum largely separates the populations of magnetic and non-magnetic CVs (Fig. 1). IPs appear to have systematically harder spectra and their kT largely differs from system to system in comparison with non-magnetic CVs.

Symbiotic systems are a heterogeneous group and are the long-period cousins of CVs and X-ray binaries (e.g. Mikolajewska & Kenyon (1992)).

IBIS, SPI, JEM-X and OMC onboard *ESA INTEGRAL* (Winkler *et al.* (2003)) enable us to obtain simultaneous information in the optical, medium X-ray, far X-ray, and gamma-ray spectral region (or at least a suitable upper limit) for each CV in each scan or field. The CV analyses represent a part of the *INTEGRAL* Core Programme (CP, topic 5.5, responsible scientist R. Hudec).

† Based on observations with *INTEGRAL*, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA.

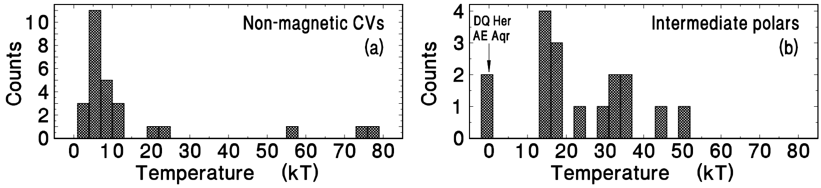

Figure 1. The statistical distributions of the temperatures (kT) in non-magnetic CVs and IPs. The data come from various published sources – mostly ASCA measurements in the 0.8–10 keV passband (e.g. Baskill *et al.* (2005), Hellier *et al.* (1996)).

2. Data source, analysis, results

The observations by *INTEGRAL* are carried out in the form of so-called science windows (ScW) which can be co-added to form a so-called mosaic. We used OSA software ver. 4.2. The fluxes were extracted by 2-D Gaussian fit using `mosaic_spec` (part of the new OSA release). For the spectral analysis, XSPEC ver. 11.3.0 and the recent response matrices (`rmf_0014`, `rmf_0007`) were employed. The results are summarized in Table 1 (the types of CVs were mostly taken from Downes *et al.* (2001)). The OMC image consists of ∼100 subwindows, each of them containing an object from a catalogue. It enables a precise photometry and provides us with the information on the optical brightness simultaneous to the far X-ray and gamma-ray band.

1223 Sgr: *INTEGRAL* caught this IP in a state of brightness lower than the average, which we call a shallow low state ($V \approx 13.4$–13.5). This is just the magnitude from which the episodes of deep low states occur (Garnavich & Szkody (1988)). We have a unique opportunity to investigate the relation between the activity in the optical and far X-ray region (Fig. 2a). In this state, when $\dot{m}$ is ∼3 times lower in comparison with the high state, the profile of the optical orbital modulation is still in good agreement with that in the high state (Jablonski & Steiner (1987)) (Fig. 2b). A period search in the residuals using the method of Scargle (1982) (code AVE) showed that the beat period (Steiner *et al.* (1981)) is still dominant over the rotational period of the WD. The orbital modulation in the 15–40 keV passband is flat, without statistically significant dips – this suggests that the blobs of overflowing matter have $N_{\rm H} < 10^{23}$ atoms cm^{-2}, taking the sizes of the error bars into account (Fig. 2c). It also implies that the observable emission region does not vary through the orbital cycle. The relation between the optical and X-ray flux was stable in all three observations over an interval of ∼400 days.

GK Per: IBIS observed this IP in quiescence between dwarf nova-type outbursts. A comparison of the measured flux with the synthetic quiescent bremsstrahlung spectrum

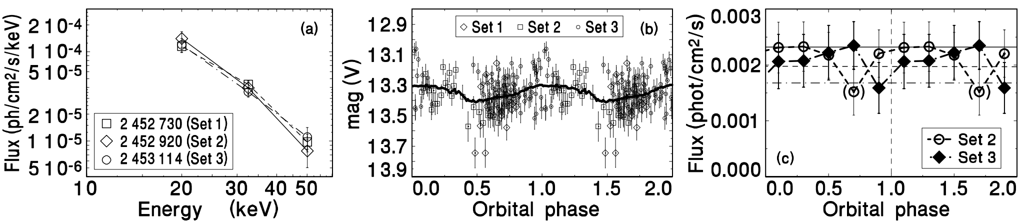

Figure 2. **(a)** Far X-ray spectra of V1223 Sgr from IBIS. The Julian Date of each spectrum is listed. **(b)** The OMC data folded with the orbital period $P_{\rm orb}$ (only images with 100 sec exp. time). The solid line represents the fit by the moving averages with the semi-interval of 0.15 phase. **(c)** IBIS 15–40 keV data binned with $P_{\rm orb}$. Several values of $N_{\rm H}$ are shown as the horizontal lines for illustration (from top to bottom: 0 atoms cm^{-2}, 5×10^{23} atoms cm^{-2}, 10^{24} atoms cm^{-2}).

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Table 1. The intensities of CVs from the IBIS *INTEGRAL* observations. T gives the type (IP – intermediate polar, P – polar, DN – dwarf nova). S refers to the state of activity (SLS – shallow low state, HS – high state, Q – quiescence). Magnitudes from OMC and from AFOEV are abbreviated as o and a, respectively. The luminosities L assume the distances given by Beuermann *et al.* (2004), Watson *et al.* (1995) and Duerbeck (1981).

CV	T	S	JD (average)	Integr. t [sec]	Flux [10^{-4} photon/cm^2/s]	L [erg/s]	mean mag
V1223 Sgr	IP	SLS	2452730	66700	14.0 ± 2.8 (15–25 keV)	1.39×10^{33}	13.44 o
					5.9 ± 0.9 (25–40 keV)	9.5×10^{32}	
		SLS	2452920	105000	11.5 ± 1.7 (15–25 keV)	1.14×10^{33}	13.36 o
					6.5 ± 0.6 (25–40 keV)	1.05×10^{33}	
		SLS	2453114	96000	11.9 ± 2.1 (15–25 keV)	1.18×10^{33}	13.32 o
					5.3 ± 0.7 (25–40 keV)	8.5×10^{32}	
V2400 Oph	IP	HS	2452920	53760	9.4 ± 1.1 (15–40 keV)		14.6–14.9 o
V1432 Aql	P	HS	2452756	37160	8.8 ± 0.9 (15–40 keV)	1.4×10^{32}	14.6 o
GK Per	IP	Q	2452848	78980	2.7 ± 1.2 (25–40 keV)	4.6×10^{32}	13.1 a

Upper limits of fluxes of non-detected CVs [10^{-4} photon/cm^2/s] (13–40 keV): V603 Aql (Type: NL) Flux=1.7 (integr.time 425000 sec); V1500 Cyg (P) Flux=1.5 (390000 sec); EM Cyg (DN) Flux=3.6 (81400 sec); EY Cyg (DN) Flux=2.8 (262000 sec); V426 Oph (DN/IP?) Flux=3.6 (24600 sec); QQ Vul (P) Flux=4.3 (24300 sec); IX Vel (NL) Flux=1.6 (511000 sec).

with the parameters from Ishida *et al.* (1992) shows a relatively plausible agreement. Our observations were obtained during the time interval between the neighbouring outbursts $\Delta t = 973$ days (∼42 percent of this interval, measured since the previous outburst). The measurements by Ishida *et al.* (1992) were obtained during $\Delta t = 983$ days (∼29 percent of this interval). This can suggest that the amount of matter arriving to the WD and the parameters of the X-ray emitting region on the WD remained almost the same during these phases of quiescence.

IX Vel: OMC covered two important events – an outburst and a shallow low state (Fig. 3a). The latter set is fitted by the code HEC13, written by Dr. Harmanec and based on the method of Vondrák (1969) and Vondrák (1977). The time scales of the decaying and rising branches of both events can be taken as comparable.

We can determine the mechanism governing this activity. The nature of variations in nova-like CVs is controversial and the thermal instability of the outer disk region is supposed also to play a role (Honeycutt (2001)). Decay rate of the decaying branch is an important parameter in this regard. The disks of dwarf novae (DNe) evolve on the thermal time scale during the final decaying branches of outbursts, which is given by the propagation of the cooling front – the magnitude of a DN decays with $\tau_{\rm D}$ here (Warner (1995); Fig. 3b). We also include $\tau_{\rm P}$ of the viscous plateau of outbursts of DNe, i.e. near the top of the outburst (AFOEV data). IX Vel lies far above the $\tau_{\rm D} - P_{\rm orb}$ relation and its disk appears to evolve on the viscous time scale, comparable to that of DNe of a similar $P_{\rm orb}$. The disk in IX Vel is thus fully ionized. Given the similar slope of the decaying and rising branch of the low state in IX Vel, we interpret this event in terms of the fluctuations of $\dot{m}$ from the donor star and to the response of the disk on the viscous time scale. The "quiescent" level before and after the outburst is the same as the bottom of the low state, which suggests that mass transfer variations can explain both events. We also find that the amplitude of the flickering decreases with the decreasing intensity of the "stable" component during the low state.

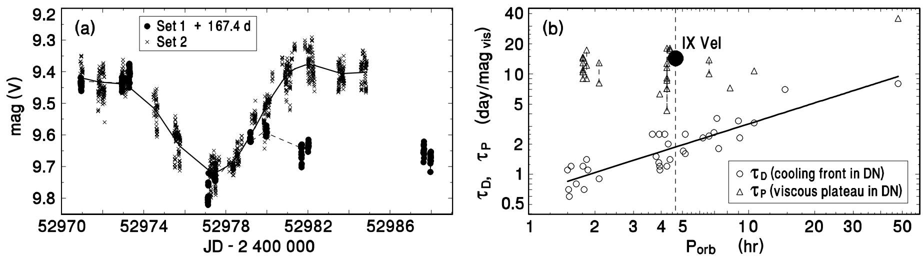

Figure 3. **(a)** Superposition of an outburst (duration < 14 days) and a short episode of a low state in IX Vel. The first packet of data preceding the outburst comes from JD 2452796 (out of the scale). **(b)** Decay rates of the decaying branches of outbursts of DNe as a function of P_{orb}. The position of IX Vel is marked.

V2116 Oph, CI Cyg and RS Oph: IBIS *INTEGRAL* proved to be suitable for the detection of the symbiotics with the hardest X-ray spectra, according to the classification by Mürset *et al.* (1996); V2116 Oph can serve as an example. OMC observations caught the symbiotic CI Cyg in quiescence ($V \approx 11$) and out of eclipse. We find the brightness to be stable at $V \approx 11$ on the time scale of days, with no flickering, in variance with RS Oph (Šimon *et al.* (2004)).

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