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Cataclysmic Variables Observed with *INTEGRAL* [1]

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Abstract We discuss selected results of observations of cataclysmic variables (CVs) and related objects by the instruments IBIS (far X-ray and gamma-ray imager) and OMC (Optical Monitoring Camera) onboard *INTEGRAL*. We concentrate on the analysis of the time behaviour of the intermediate polar (IP) V1223 Sgr, seen simultaneously by IBIS and OMC in a state which we call a shallow low state. We present far X-ray spectra (E up to 60 keV) and the relation between far X-ray and optical flux. We demonstrate the stability of this relation and of the profile of the X-ray spectra during this state over an interval of 400 days. We also present far X-ray observations of some other magnetic CVs and show that the systems with magnetized white dwarf (like polars and IPs) appear to be the most promising CVs for *INTEGRAL*. We also include the examples of the OMC light curves and show that the outburst and a low state of IX Vel are caused by the mass transfer variations, and not by the thermal instability of the disk.

Key words: binaries: close— binaries: general— Stars: magnetic fields— novae, cataclysmic variables— Stars: individual: V 1223 Sgr

1 INTRODUCTION

Cataclysmic variables (CVs) are close binary systems in which mass accretion from a late-type main-sequence, lobe-filling star onto a compact object (white dwarf (WD) in our case) occurs. Generally, CVs are X-ray sources. Their observed X-ray and optical activity, luminosity and spectrum 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 with disks through intermediate polars (IPs) to polars in which the disk is disrupted completely. Bremsstrahlung is the dominant process for the X-ray radiation of CVs (see Warner (1995) for a review).

Symbiotic systems are a heterogeneous group and are the long-period cousins of CVs and X-ray binaries (e.g. Mikolajewska & Kenyon 1992). The accretor is usually a WD, but a neutron star or a main-sequence star are present in some systems.

Four instruments (far X-ray and gamma-ray imager IBIS, spectrometer SPI, X-ray monitor JEM-X, optical monitoring camera 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 *I*NTEGRAL Core Programme (CP, topic 5.5, responsible scientist R. Hudec). The numbers of known CVs and symbiotics observable during Galactic Plane Scans (GPS) were discussed by Šimon et al. (2004a).

2 OBSERVATIONS

The observations by *INTEGRAL* are carried out in the form of so-called science windows (ScW), each of them lasting for about 30 min. All the onboard X-ray and gamma-ray instruments carry out uninterrupted

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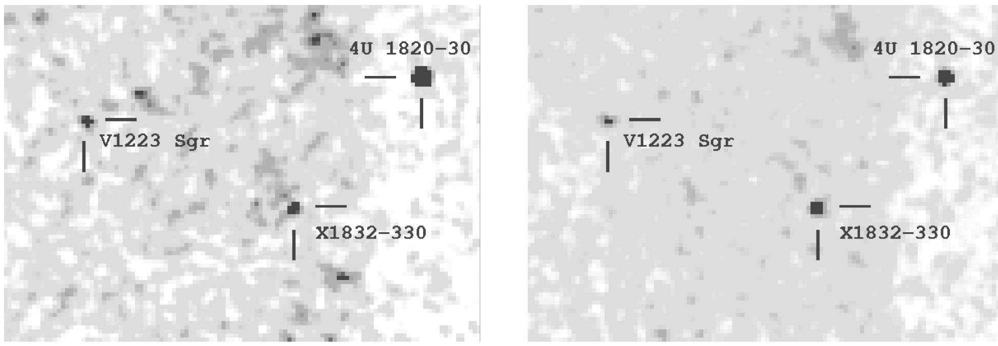

Fig. 1 Co-added frames of the field of V1223 Sgr obtained by IBIS, with the starting exposure time in JD 2452730.2 and the integration time of 66700 s. Left panel: 15–25 keV passband. Right panel: 25–40 keV passband. Size of the field is $9.5^{\circ} \times 6.8^{\circ}$. North is up, East to the left. The positions of several neighbouring bright X-ray sources are labeled, too.

observation while OMC secures a series of images during this period. The individual ScWs of a given field can be co-added to form a so-called mosaic, suitable for an identification and measurement of fainter objects.

It emerges that CVs can be positively identified in the IBIS mosaics, particularly the magnetic ones. The energy bands of IBIS can be defined by the user to obtain sufficient signal to noise ratio and, at the same time, sufficient energy resolution for the study of continuous spectral profiles. We used OSA software ver. 4.2 for this analysis. 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 OMC image consists of ~100 subwindows, each of them containing an object from a catalogue. It enables a precise photometry, including an analysis of rapid light variations of brighter CVs. The exposure times are 10 s, 30 s and 100 s. We found that only the 100 s exposure times yield sufficiently small observational errors to be useful for the study of rapid brightness variations in CVs brighter than about 13.5–14 mag(V) while the 30 s exposure times can be included for the study of objects brighter than ~11.5–12 mag(V). OMC also provides us with the information on the optical brightness simultaneous to the far X-ray and gamma-ray band.

3 RESULTS

Here we present selected results of our observations of CVs and related systems with IBIS and OMC onboard *INTEGRAL*.

1223 Sgr: This IP displays a strong long-term activity (e.g. Garnavich & Szkody 1988). AFOEV observations show that *INTEGRAL* (Fig. 1) caught it in a state of brightness definitely lower than the average, which we call a shallow low state ($V \approx 13.5$). We have a unique opportunity to investigate the relation between the activity in the optical and far X-ray region (Fig. 2a) and obtain far X-ray spectra (Fig. 2b). Even in this state, both the profile of the optical modulation with the orbital period $P_{\rm orb}$ and the phase of the minimum light are in good agreement with those determined by Jablonski & Steiner (1987) (Fig. 2c). A period search in the residuals was undertaken using Scargle method (Scargle 1982) included in the code AVE. The beat period $P_{\rm beat} \approx 794$ s (Steiner et al. 1981) is found to be still dominant although also the rotational period of the WD, $P_{\rm rot} \approx 746$ s, (Osborne et al. 1985) can be marginally present.

GK Per: This IP (e.g. Watson et al. 1985) exploded as a classical nova in 1901. Fluctuations by ~1 mag and later dwarf nova-type outbursts appeared after return to quiescence (e.g. Hudec 1981, Šimon 2002). These outbursts are accompanied by a large increase of the medium X-ray luminosity (e.g. King et al. 1979, Šimon 2002).

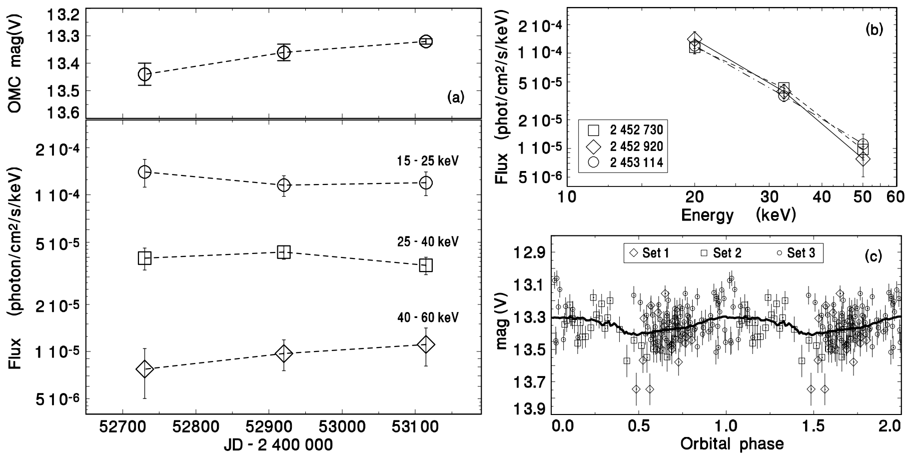

Fig. 2 **(a)** Time variations of the V band magnitude and far X-ray intensity of V1223 Sgr. The points in each panel are connected by the line only for convenience. **(b)** Far X-ray spectra of V1223 Sgr from IBIS. The Julian Date of each spectrum is listed. **(c)** The OMC data folded with the orbital period $P_{\rm orb}$ (only images with 100 s exp. time). The solid line represents the fit by the moving averages with the semi-interval of 0.15 phase.

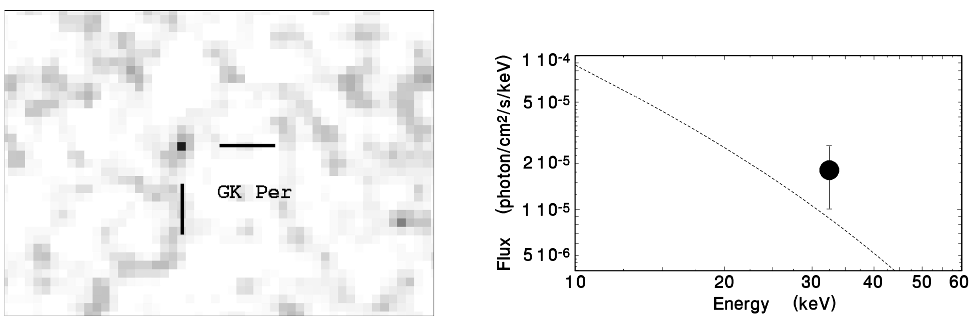

Fig. 3 Left panel: Co-added frames of the field of GK Per obtained by IBIS on 19th March 2003 and 27–29th July 2003 (25–40 keV). The total integration time is 78980 s. Size of the field is $4.1^{\circ} \times 3.0^{\circ}$. North is up, east to the left. Right panel: comparison of the measured flux of GK Per in the IBIS image and the synthetic bremsstrahlung spectrum with the parameters from Ishida et al. (1992).

IBIS observed GK Per on two occasions in the interval of quiescence between the outbursts. The system was positively identified in the 25–40 keV band (Fig. 3). A comparison of the measured flux with the synthetic quiescent bremsstrahlung spectrum with the parameters from Ishida et al. (1992) (normalization 0.0039 ± 0.0002 photon cm^{-2} s^{-1} keV^{-1}, $kT = 32$ keV, $N_{\rm H} = 10^{22}$ cm^{-2}) shows a relatively plausible agreement (Fig. 3). We note that our observations were obtained during the time interval between the neighbouring outbursts $\Delta t = 973$ days; they started at $\sim$42 percent of this interval (measured since the previous outburst). The reference spectrum in Figure 3 was determined from the measurements obtained during $\Delta t = 983$ days (they started at $\sim$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 the quiescent intervals.

V1432 Aql: This is a desynchronized polar, whose $P_{\rm orb} = 3.37$ hr differs from $P_{\rm rot}$ by $\sim$0.3 percent (Patterson et al. 1995). The system was identified in the 15–40 keV band of IBIS (Fig. 4). The flux in the

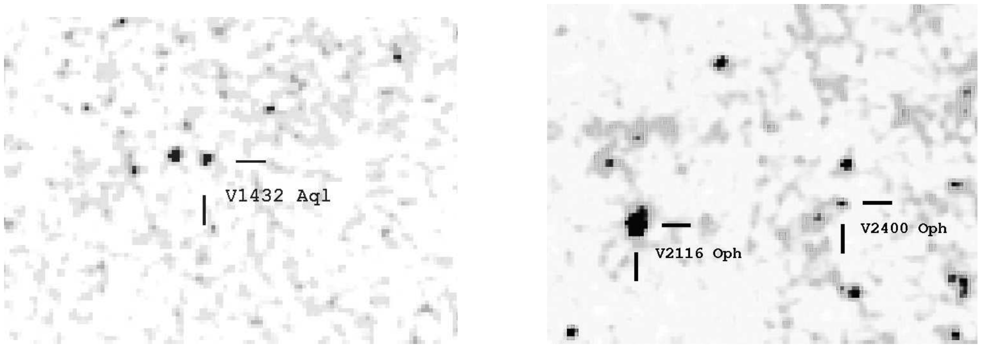

Fig. 4 Left panel: Co-added frames of the field of V1432 Aql obtained by IBIS, starting in JD 2452756 (15–40 keV). The total integration time is 37160 s. Size of the field is $9.4^\circ \times 6.9^\circ$. Right panel: Co-added frames of the field of V2400 Oph obtained by IBIS in JD 2452732, JD 2452920 and JD 2453054 (15–40 keV). The total integration time is 53760 s. Size of the field is $9.2^\circ \times 7.2^\circ$. North is up, east to the left in both panels.

15–40 keV passband is $8.81 \times 10^{-4} \pm 0.90 \times 10^{-4}$ photon cm^{-2} s^{-1}. OMC showed the mean optical brightness of 14.6 mag(V) during the *INTEGRAL* observations.

V2400 Oph: This is a diskless IP with $P_{\rm orb} = 3.4$ hr, $P_{\rm rot} = 927$ s and the beat period $P_{\rm beat} = 1003$ s (Buckley et al. 1997). IBIS observed V2400 Oph on three occasions and the system was identified in the 15–40 keV band. Since the OMC data show a stable level of the optical brightness between 14.6–14.9 mag(V), a mosaic composed of all the data was made (Fig. 4). The flux in the 15–40 keV passband is $9.37 \times 10^{-4} \pm 1.14 \times 10^{-4}$ photon cm^{-2} s^{-1} for the combined measurements.

IX Vel: This object was identified as a nova-like system by Garrison et al. (1984). It was not detected in IBIS mosaic; the upper limit of the 13–40 keV flux is 1.6×10^{-4} photon cm^{-2} s^{-1} (integration time 511000 s). OMC covered two important events of this system – an outburst with the duration of less than 14 days and a short episode of a low state. Superposition of both events is shown in Fig. 5. The latter set is fitted by the code HEC13, written by Dr. Harmanec and based on the method of Vondrák (1969, 1977). It can be seen that 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 $\tau_{\rm D}$, measured in days mag^{-1}, is an important parameter in this regard. The values of $\tau_{\rm D}$ of non-magnetic dwarf novae (DNe) as a function of $P_{\rm orb}$, taken from Warner (1995), are displayed in Fig. 5. The disk evolves on the thermal time scale during the final decaying branches of outbursts in DNe, which is given by the propagation of the cooling front. On the contrary, we find $\tau_{\rm D}$ of IX Vel to lie far above the relation for DNe. The disk in IX Vel thus appears to evolve on the viscous time scale, which means that the transition to the low state is not caused by the cooling front, but can be attributed to the variations of the mass transfer rate from the donor star. 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.

CI Cyg and RS Oph: The eclipsing symbiotic system CI Cyg ($P_{\rm orb} = 855$ days (Aller 1954)) undergoes occasional outbursts with an amplitude of $\sim$2 mag(V) (e.g. Ruiz 1992). OMC observations caught it in quiescence ($V \approx 11$) and out of eclipse. We searched for rapid and non-orbital variations and found the brightness to be stable at $V \approx 11$ on the time scale of days, with no flickering. This is important in comparison with RS Oph (Šimon et al. 2004b).

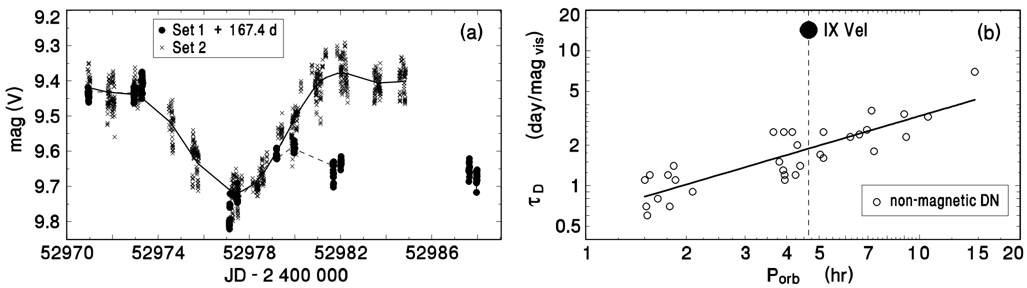

Fig. 5 **(a)** Superposition of an outburst (duration < 14 days) and a short episode of a low state in IX Vel. The first packet of data preceding the outburst comes from JD 2452796 (out of the scale). **(b)** Decay rate of the decaying branches of outbursts of non-magnetic DNe as a function of $P_{\rm orb}$. The position of IX Vel is marked.

4 CONCLUSIONS

INTEGRAL is suitable for the detection and observation of CVs with the hardest X-ray spectra. This is true also for the symbiotics with the hardest X-ray spectra according to the classification by Mürset et al. (1996); V2116 Oph in the IBIS image of V2400 Oph can serve as an example. The OMC V band observations are helpful even for those CVs too faint in far X-ray passbands to be detected by IBIS. Simultaneous IBIS and OMC data enable us to investigate the relation between far X-ray flux and optical magnitude of a given CV and enable us to relate the processes in the different regions of the system.

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DISCUSSION

NICOLA MASETTI: Can you give an order-of-magnitude average luminosity (in the X-ray bands observed with *INTEGRAL*) for these cataclysmic variables?

ŠIMON: We can say that the typical luminosities of IPs detected by IBIS, namely GK Per, V1432 Aql and V1223 Sgr, are of the order of $10^{32} - 10^{33}$ erg s^{-1} in the soft passbands of this instrument.