Broad-band characteristics of seven new hard X-ray selected cataclysmic variables

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ABSTRACT

We present timing and spectral analysis of a sample of seven hard X-ray selected Cataclysmic Variable candidates based on simultaneous X-ray and optical observations collected with XMM-Newton, complemented with Swift/BAT and INTEGRAL/IBIS hard X-ray data and ground-based optical photometry. For six sources, X-ray pulsations are detected for the first time in the range ∼ 296 − 6098 s, identifying them as members of the magnetic class. Swift J0927.7-6945, Swift J0958.0-4208, Swift J1701.3-4304, Swift J2113.5+5422, and possibly PBC J0801.2-4625, are Intermediate Polars (IPs), while Swift J0706.8+0325 is a short (1.7 h) orbital period Polar, the 11th hard X-ray selected identified so far. X-ray orbital modulation is also observed in Swift J0927.7-6945 (5.2 h) and Swift J2113.5+5422 (4.1 h). Swift J1701.3-4304 is discovered as the longest orbital period (12.8 h) deep eclipsing IP. The spectra of the magnetic systems reveal optically thin multi-temperature emission between 0.2 and 60 keV. Energy dependent spin pulses and the orbital modulation in Swift J0927.7-6945 and Swift J2113.5+5422 are due to intervening local high density absorbing material (N_H ∼ 10^{22−23} cm^{-2}). In Swift J0958.0-4208 and Swift J1701.3-4304, a soft X-ray blackbody (kT ∼ 50 and ∼ 80 eV) is detected, adding them to the growing group of “soft” IPs. White dwarf masses are determined in the range ∼ 0.58 − 1.18 M_☉, indicating massive accreting primaries in five of them. Most sources accrete at rates lower than the expected secular value for their orbital period. Formerly proposed as a long-period (9.4 h) novalike CV, Swift J0746.3-1608 shows peculiar spectrum and light curves suggesting either an atypical low-luminosity CV or a low mass X-ray binary.

Key words: novae, cataclysmic variables - white dwarfs - X-rays: individual: Swift J0706.8+0325, X-rays: individual: Swift J0746.3-1608 (aka 1RXS J074616.8-161127), X-rays: individual: Swift J0927.7-6945, X-rays: individual: Swift J0927.7-6945, X-rays: individual: Swift J0958.0-4208, X-rays: individual: PBC J0801.2-4625 (aka 1RXS J080114.6-462324), X-rays: individual: Swift J1701.3-4304 (aka IGR J17014-4306), X-rays: individual: Swift J2113.5+5422.

1 INTRODUCTION

Cataclysmic variables (CVs) are close binary stellar systems where a compact primary, a white dwarf (WD), accretes matter from a low mass (M ≲ 1 M_☉) Roche lobe filling main-sequence or subgiant secondary. About one quarter of the whole CV class host strongly magnetized WDs (10^5 < B < 2.4 × 10^8 G). The magnetic systems (MCVs) are further divided in two subclasses, depending on the WD magnetic field intensity and degree of synchronism (see e.g. Cropper 1990; Warner 1995; Hellier 2014; Ferrario, de Martino & Gänsicke 2015; Mukai 2017). Those showing intense optical/near-infrared (nIR) polarised emission, the so-called polars (or AM Her stars), have stronger magnetic fields (B ≳ 10^7 G) which synchronize the WD rotation with the orbital period.
with a few exceptions do not show detectable polarized optical/nIR magnetic field strengths \( B \). Both groups are characterised by periodic X-ray emission at the WD rotational period, a clear signature of magnetic accretion. IPs mainly populate the orbital period distribution above the so-called 2–3 hr orbital period gap, while polars are generally found below it (Warner 1995), suggesting that IPs may eventually evolve into polars (Norton, Wynn & Somerscales 2004).

The way in which the material lost from the companion is accreted by the WD, mainly depends on the WD magnetic field intensity. Eventually, when the flow gets closer to the WD, it is magnetically channelled along the field lines. Due to the strong dipolar field in polars, matter lost by the companion is accreted directly from a stream, while IPs may accrete from a stream or through a disc, depending on the magnetic moment and the degree of asynchronism (Norton, Wynn & Somerscales 2004; Norton et al. 2008). In the latter case accretion proceeds from the disc to the WD surface on arc-shaped accretion curtains (Rosen, Mason & Cordova 1988). Disc-overflow (a hybrid accretion mode), may also occur depending on the mass accretion rate (Holliday 1999; Norton et al. 1997).

Since the velocities in the accretion flow are supersonic a stand-off shock forms. The temperature in the post shock region is high \( \sim 10 – 80 \) keV and the flow cools and slows down via bremsstrahlung (hard X-ray) and cyclotron (optical/nIR) radiation (Aizu 1973; Wu, Channamag & Shaviv 1994; Cropper et al. 1999). The efficiency of the cooling mechanisms depends on the WD magnetic field intensity and the local mass accretion rate (Woelk & Beuermann 1994; Fischer & Beuermann 2001). The hard X-rays and cyclotron emission are partially absorbed and reflected from the WD surface. The thermalised emission from the WD pole gives rise to a non-negligible soft \( \sim 20 – 60 \) eV X-ray blackbody component, formerly believed a characteristic of the polar systems only (Beuermann 1999). The presence of this component has been challenged by XMM-Newton observations showing an increasing number of polars without it (see e.g. Ramsay & Cropper 2004; Ramsay et al. 2009; Bernardini et al. 2014). On the other hand, while ROSAT initially only a handful of “soft” IP systems (Haberl & Motch 1995), XMM-Newton has later revealed that a soft X-ray blackbody is also present in a non-negligible number of IPs (Evans & Holliday 2007; de Martino et al. 2004; Anzolin et al. 2008; de Martino et al. 2008; Bernardini et al. 2012). Compton reflection from the WD surface, considered nearly neutral, produces a non-negligible Fe \( K \alpha \) line at 6.4 keV as observed in all MCVs (Ezuka & Ishida 1999), as well as a Compton reflection continuum peaking at energies above 10 keV (Done & Magdziarz 1998), which was unambiguously detected in recent joint XMM-Newton and NuSTAR observations of three bright IPs (Mukai et al. 2015). Complex absorption from neutral material in the dense (\( N_{\text{H}} \) up to \( 10^{23} \) cm\(^{-2}\) ) pre-shock flow, partially covering the X-ray emitting pole, is an additional complication in interpreting the X-ray spectra and spin modulations of MCVs (Rosen, Mason & Cordova 1988; Mukai, Ishida & Osborne 1998). Moreover, the detection of absorption edges of ionised Oxygen or Iron in a few IPs (Mukai et al. 2001; de Martino et al. 2008; Bernardini et al. 2012) testifies that the accretion flow can also be ionised also in MCVs, besides low mass X-ray binaries.

Thanks to the deep hard X-ray surveys carried out by INTEGRAL and Swift satellites above 20 keV, and the numerous multiwavelength followup (see e.g. Masetti et al. 2013 and reference therein) the number of MCVs increased rapidly in the last years, the majority being identified as magnets of the IP class, with a few polars and a handful of non-magnetic systems (Barlow et al. 2004; Bird et al. 2010; Cusumano et al. 2010; Baumgartner et al. 2013). The role of these hard X-ray emitting CVs as dominant contributors to the low-luminosity \( \lesssim 10^{33} \text{erg s}^{-1} \) X-ray source population in the galactic ridge (GRXE) and Galactic centre is a greatly debated topic for a decade (Muno et al. 2004; Sazonov et al. 2004; Revnivtsev et al. 2009; 2011; Warwick, Byckling & Pérez-Ramírez 2014; Perez et al. 2015; Hailey et al. 2016). Whether the low-luminosity component is due to non-magnetic CVs or to a still to be discovered large population of IPs accreting at low rates has yet to be established. This would require higher space densities of MCVs than those, still very uncertain, obtained from current observations (see Reis et al. 2013; Pretorius & Mukai 2014, and reference therein). In this respect, the identification of new systems is important to increase the statistics.

We here present the analysis of simultaneous X-ray and optical data of seven recently identified candidates, to unambiguously confirm them as magnets through the search for X-ray pulsations and the study of their broad-band spectral properties. Our source sample consists of Swift J0706.8+0325, Swift J0746.3-1608, PBC J0801.2-4625, Swift J0927.7-6945, Swift J0958.0-4208, Swift J1701.3-4304, and Swift J2113.5+5422 (hereafter J0706, J0746, J0801, J0927, J0958, J1701, and J2113, respectively). Their magnetic candidacy was only based on optical spectroscopic follow-ups (Masetti et al. 2013; Thorstensen & Halpern 2013; Parisi et al. 2014; Halpern & Thorstensen 2015, and references therein). Spectroscopic orbital periods were determined for J0706 (1.7 hr; Halpern & Thorstensen 2015) and J0746 (9.4 hr; Thorstensen & Halpern 2013), suggesting a Polar and a novalike, respectively.

2 OBSERVATIONS AND DATA REDUCTION

2.1 XMM-Newton observations

The sources were observed between 2015-06-05 and 2016-04-01 by XMM-Newton with the European Photo Imaging Cameras (EPIC: PN, MOS1 and MOS2 Strüder et al. 2001; Turner et al. 2011; Watanabe, Byckling & Pérez-Ramírez 2014; Perez et al. 2015), as main instruments, complemented with simultaneous optical monitor (OM, Mason et al. 2001) photometry. The details of the observations are reported in Table I. Data were processed using the Science Analysis Software (SAS) version 15.0.0 and the latest calibration files available in 2016 February.

2.1.1 The EPIC and RGS data

For the EPIC data, source photon event lists and spectra were extracted from a circular region of radius 40 arcsec. Background photons were taken from a nearby region of the sky clear from sources contamination, in the same CCD where the source lies, avoiding CCD gaps. For the spectral analysis, high particle background epochs were removed in all instruments, while for the timing analysis, we used the whole data set when possible.

Background-subtracted light curves were also generated with the task EPICLCORR in the ranges \( 0.3 – 12 \) keV, \( 0.3 – 1 \) keV, \( 1 – 3 \) keV, \( 3 – 5 \) keV and \( 5 – 12 \) keV, with different bin size, depending
on the source and background flux. The event arrival times were corrected to Solar system barycenter by using the task BARYCEN. Spectra were rebinned before fitting with the task SPECGROUP, in order to have a minimum of 50 and 25 counts in each bin for PN and MOSs, respectively, and to prevent oversampling of the energy resolution by more than a factor of three. Spectra were also extracted as a function of the source rotational phase and of the orbital phase, when applicable. The response matrix and the ancillary files were generated using the tasks RMTGEN and AREGEN. The spectral fits were made with XSPEC version 12.8.2 (Arnaud 1996).

All sources except J0706, are too faint for a meaningful anal-

| Source Name | Coordinates (J2000) | Telescope | OBSID | Instrument | Date yyyy-mm-dd | UT_{start} hh:mm | T_{exp}^a ks | Net Source Count Rate c/s |
|-------------|--------------------|-----------|-------|------------|-----------------|-----------------|-------------|--------------------------|
| Swift J0706.8+0325 | XMM-Newton 0761120501 | EPIC-PN | 2015-10-25 | 15:00 | 39.6 | 0.896 ± 0.006 |
| RA=07:06:48:90 | Dec=+03:24:47.3 | EPIC-MOS1 | 2015-10-25 | 17:03 | 32.0 | 0.237 ± 0.003 |
| Swift J0746.3-1608 | XMM-Newton 0761120401 | EPIC-PN | 2016-04-01 | 08:29 | 34.5 | 0.136 ± 0.003 |
| RA=07:46:17:13 | Dec=-16:11:27.8 | EPIC-MOS1 | 2016-04-01 | 08:23 | 34.7 | 0.035 ± 0.001 |
| Swift J0801.2-4625 | XMM-Newton 0761120301 | EPIC-PN | 2015-12-04 | 18:50 | 30.0 | 0.747 ± 0.006 |
| RA=08:01:17:03 | Dec=-46:23:27.5 | EPIC-MOS1 | 2015-12-04 | 18:28 | 31.7 | 0.192 ± 0.003 |
| Swift J0927.7-6945 | XMM-Newton 0761120901 | EPIC-PN | 2016-05-06 | 01:00 | 31.6 | 0.471 ± 0.004 |
| RA=09:27:53:12 | Dec=-69:44:42.0 | EPIC-MOS1 | 2016-05-06 | 00:47 | 31.7 | 0.140 ± 0.002 |
| Swift J0958.0-4208 | XMM-Newton 0761120101 | EPIC-PN | 2015-05-05 | 04:56 | 37.9 | 0.684 ± 0.007 |
| RA=09:57:50:64 | Dec=-42:08:35.5 | EPIC-MOS1 | 2015-05-05 | 04:34 | 38.2 | 0.204 ± 0.003 |
| Swift J1011.3-4304 | XMM-Newton 0761120701 | EPIC-PN | 2015-09-22 | 15:25 | 30.0 | 0.896 ± 0.006 |
| RA=17:01:28:15 | Dec=-43:06:12.3 | EPIC-MOS1 | 2015-09-22 | 15:02 | 31.7 | 0.237 ± 0.003 |
| Swift J2113.5+5422 | XMM-Newton 0761120701 | EPIC-PN | 2015-11-17 | 17:28 | 36.3 | 1.021 ± 0.006 |
| RA=21:13:35:40 | Dec=+54:22:32.8 | EPIC-MOS1 | 2015-11-17 | 17:05 | 38.0 | 0.323 ± 0.003 |

Notes:

a Coordinates of the optical counterpart.

b Net exposure time.

c Large window mode (thin filter applied).

d Small window mode (thin filter applied).

e Fast window mode. The central wavelength of the B filter is 4500 Å.

f OM instrumental magnitude.

\( ^g \) All available pointings collected from 2004 December to 2010 September are summed together.

\( ^h \) All observations available between 2009-08-28 and 2014-06-20 (observation id: 49197, 38960, 40698, 41163, and 90159) are summed together.

\( ^i \) Full frame mode (thin filter applied).

\( ^j \) Fast window mode. The central wavelength of the V filter is 5430 Å.

\( ^k \) All available pointings collected from 2003-04-05 to 2014-12-20 are summed together.
ysis with the RGS. For that source, the RGS1 and RGS2 spectra from the standard SAS pipeline were used (Table 1).

2.1.2 The Optical Monitor photometry

In all observations the OM was operated in fast window mode using the B-band (3900–4900 Å) filter, except for J0801 and J2113 where the V-band (5100–5800 Å) filter was used due to bright source in their field of view. The background subtracted light curves were generated with the task OMFCCHAIN, with different bin times (~1–10 s) depending on the source flux, and then barycentric corrections were applied.

2.2 The Swift observations

BAT has built up an all-sky map of the hard X-ray sky (14–195 keV), thanks to its wide field of view. For all sources, with the exception of J0801 for which no spectrum is available, we used the archival eight-channel spectra from the first 70 months of monitoring (Baumgartner et al. 2013) available at the NASA GSFC site. The sources under study are all detected up to energies ~ 80 keV up to which we restrict our spectral analysis.

We also used XRT archival data to study the long term variability of two sources (J0746 and J0801). For this scope we used the lightcurves and spectra from the XRT products generator (Evans et al. 2009) at the UK Swift Science Data Centre at the University of Leicester.

2.3 The INTEGRAL observations

For J0801 we extracted the INTEGRAL/IBIS spectrum from all the 1845 public INTEGRAL pointing with RA ∈ [109, 135] and Dec ∈ [−53, 36]. The Offline Analysis Software v. 10.2 distributed by the ISDC (Courvoisier et al. 2003) was used. We built a response with four logarithmically spaced bins between 20 and 100 keV and extracted the source flux using the standard spectral extraction. We derived a sky model from a mosaicked significance map in the 20–100 keV band, which includes 39 sources, and an average mission background, retrieved from the calibration files. The spectral analysis of J0801 is further restricted below 80 keV.

2.4 Optical ground based photometry

The detection of deep X-ray and optical eclipses in J1701 (Section 3.6) motivated the search for its orbital period using optical ground-based photometry.

J1701 was repeatedly observed during ten days with the 1-m network of robotic optical telescopes in the Las Cumbres Observatory (LCO), from 2016-06-06 20:29:08 UT to 2016-06-16 03:34:33 UT. Six telescopes were used, located at three sites, Cerro Tololo (Chile), South African Astronomical Observatory (SAAO), Sutherland (South Africa) and Siding Spring (Australia). Imaging was obtained in the Sloan Digital Sky Survey (SDSS) g'–band with exposure times of 40 s. The coverage was typically 40 minutes about three times in 24 hours. A total of 328 usable images were acquired. The automatic Las Cumbres Observatory (LCO) pipeline BANZAI provides users with bias and flat-field corrected science images. Additional photometry was acquired during seven nights for about 5 hours consecutively from 2016-07-27 00:05:13 UT to 2016-08-07 06:08:00 UT with the robotic 0.6 m INAF REM telescope in La Silla, Chile (Zerbì, Chincarini & Ghisellini 2004). The telescope is equipped with the ROSS2 camera that performs simultaneous exposures in the Sloan filters g', r', i' and z' and with the REMIR camera (Conconi, Cuniffe & D’Alessio 2004) covering simultaneously the near-IR band. Integration times were 150 s for all optical filters and a dithering of 5 exposures of 60 s each was used for the REMIR J-band. Both ROSS2 and REMIR data sets were reduced using standard routines of IRAF to perform bias and flat-field corrections. Due to the low response of the z’ filter the corresponding images have not been analysed. For the REMIR observations the five dithered images were merged into a single frame. A total of 483 useful science images were secured in each g’, r’, i’ filters while 251 were obtained in the J band.

Aperture photometry was performed on both LCO and REM data sets optimizing aperture radius and sky subtraction by adopting annuli of different sizes. Comparison stars were used to check and to correct for variable sky conditions. REM/ROSS2 and REMIR photometry was calibrated using the Sloan standards SA 104 428, SA 114 531 and SA 093 317 observed each night in July and August, respectively, whose near-IR magnitudes are also tabulated in the 2MASS catalogue (Skrutskie et al. 2006). The LCO photometry was instead calibrated using three comparison stars with known g’ magnitudes. Both data sets in the g’ band agree within 9 per cent. Average magnitudes are: g’=16.50 ± 0.02, r’=15.389 ± 0.009, i’=14.999 ± 0.008, and J=13.31 ± 0.02 mag.

J1701 is also identified in the AAVSO Photometric All-Sky Survey (APASS) as GDS J1701281-430612 (Henden et al. 2016). It was recently observed by AAVSO from 2016-09-20 23:15:19 UT to 2016-10-27 10:46:14 UT with several filters. For our purposes, we selected the most dense coverage in the V-band, including clear (unfiltered) reduced to V-band observations, totaling 3943 photometric measures. The average V magnitude is 16.05 ± 0.04. All light curves were corrected to the Solar system barycentre.

3 DATA ANALYSIS

In this section, we describe the common procedures adopted for all sources to perform the timing and spectral analysis. We present the results, for each source individually, in Section 4.

3.1 Timing analysis

Light curves in the 0.3–12 keV range (PN and MOS) and in the optical OM B or V bands were first inspected for short and long-term variability (Figure 1). Then power spectra were computed to identify periodic signals in the two energy domains. A phase-fitting technique (see e.g. Dall’Osso et al. 2003 for details on the technique), was then used for an accurate period determination of the stronger signal. In case of additional significant peaks, the periods were determined using the FTOOLS task EFSEARCH (Blackburn 1995).

We interpreted the pulsation associated with the main peak in the power spectrum as the WD spin period (P WD), the lower signals

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1 http://swift.gsfc.nasa.gov/results/ba70mon/
2 http://swift.gsfc.nasa.gov/results/bs70mon/
3 http://www.rem.inaf.it
4 http://www.ipac.caltech.edu/2mass/
5 http://www.aavso.org/apass
6 http://heasarc.gsfc.nasa.gov/ftools/
to sidebands (P_{X,side}^\infty) and, when present, to the orbital (P_{\Omega,orb}^\infty) periods. The most common and stronger sideband observed in IPs is the beat (\omega - \Omega) between the spin and the orbital (\Omega) periods and, when present, we used it to estimate the orbital period.

For those sources displaying detectable orbital variability, a fit using one or more sinusoids (the fundamental plus possible harmonics) was performed to estimate the orbital period in the X-ray (P_{\Omega,orb}^\infty) and optical (P_{opt}^{\infty}) bands. The two procedures were verified to give consistent results.

Spectral variations along the spin period were first inspected by folding at P_n^\infty the background subtracted source light curves extracted in five energy bands: 0.3–1, 1–3, 3–5, 5–12 keV and computing the hardness ratios (HR) defined as the count rate ratio in each phase bins between two selected energy ranges. A quantitative analysis (Table 2, second column) was then performed by fitting the pulses in the above bands with a Fourier sine series truncated at the highest significant harmonic. For each energy interval, the pulsed fraction was computed as: $\text{PF} = (A_{\text{max}} - A_{\text{min}})/(A_{\text{max}} + A_{\text{min}})$, where $A_{\text{max}}$ and $A_{\text{min}}$ are respectively the maximum and minimum amplitudes of the sinusoid at the fundamental frequency.

### 3.2 Spectral analysis

The study of the broad-band (0.3–80 keV) spectral properties of each source was first accomplished on the grand-average PN, MOS1 and MOS2 spectra together with the corresponding Swift-BAT or INTEGRAL-IBIS spectra fitted simultaneously. Calibration discrepancies between different instruments were taken into account by including in the fits an inter-calibration constant which only for the PN is fixed to one. This constant also accounts for the non simultaneity of the BAT/IBIS spectra with those from the EPIC cameras and so for possible source long-term variability. All model parameters were linked between different instruments expect the multiplicative constants.

The sources under study display thermal spectra and most of them also show emission features at the iron complex. These are generally observed in the MCVs which have multiphase spectra locally absorbed by high dense cold material (see e.g. Done, Osborne & Beardsmore 1995; Ezuka & Ishida 1999; Beardmore, Osborne & Hellier 2000; de Martino et al. 2004; Anzolin et al. 2008; Bernardini et al. 2012; Mukai et al. 2015).

Therefore, the spectra were fitted with a composite model consisting of one or more optically thin plasma components (BREMS, MEKAL or CEMEK in XSPEC), with metal abundances (A_\text{Z}) with respect to Solar from Wilms, Allen & McCray (2000), left free to vary, absorbed by a total (PHABS) and one or two partial (PCfabs) covering columns and a narrow Gaussian line fixed at 6.4 keV to account for the fluorescent Fe Kα feature. When needed, a blackbody component (BBODY) was also included to model a soft excess in the residuals. Despite the presence of the 6.4 keV line feature the inclination of a reflection component (REFLECT) does not improve the fit quality in any of the sources under study, indicating that higher quality spectra above 10 keV are needed (see also Mukai et al. 2015).

Additionally, to obtain a more reliable estimate of the mass of the accreting WD, the broad-band continuum spectra were also fitted with the more physical post-shock region (PSR) model developed by Suleimanov, Revnivtsev & Ritter (2005). This model takes into account both temperature and gravity gradients within the PSR in bremstrahlung dominated regimes where cyclotron cooling is negligible, and thus applicable to those sources identified as IPs and, with caution, also to a low-field polar (see Sect. 4.1.2). To this purpose, for those sources showing soft complexities, the spectra were analysed above 1–3 keV to avoid the effect of absorption and heavily rebinned to smear emission lines, except the iron line complex, which is accounted for by a broad Gaussian.

To unveil the role of spectral parameters in producing the X-ray spin/orbital modulations, a pulse-phase spectroscopy (PPS) analysis was performed on the EPIC spectra extracted at spin/orbital maximum and minimum, which were fitted separately. For each source we adopted the spectral models and parameters obtained from the phase average spectral fits, fixing the column density of the total absorber and the metal abundance at their best fit values. All other parameters were left free to vary in the spin PPS analysis. In the orbital PPS analysis only the partial covering absorbers and the MEKAL(s) normalization(s) (n_c and n_n) were left free to vary when this extra free component is statistically significant (F-test verified).

### 4 RESULTS

#### 4.1 Swift J0706.8+0325

J0706 has been recently identified by Halpern & Thorstensen (2015), where it appears as PBC J0706.7+0327, as a short (1.7 h) orbital period CV and proposed as a polar based on its emission line variations and large amplitude optical modulation.

##### 4.1.1 Timing analysis

The X-ray light curve covers about seven cycles of an almost on-off modulation, although the count rate does not drop to zero at minima (Figure 1). From a multi-sinusoidal fit to reproduce the shape of the modulation, we get a period of 6135 ± 5 s, which is within 2σ consistent with the more accurate orbital period (6126.36 ± 0.10 s) determined by Halpern & Thorstensen (2015) with optical spectroscopy (Table 2). This allows to interpret the X-ray period as the spin of the WD which is synchronised with the binary orbit. Thus, J0706 is unambiguously identified as a polar system. The OM B-band photometry being affected by technical problems is not used in the present study.

The X-ray light curves at different energies were folded using the spectroscopic ephemeris of Halpern & Thorstensen (2015). The modulation shows a broad asymmetric maximum extending ∼0.6 in phase. It is structured below 3 keV with a lower count rate during the first half of the maximum and a dip at φ ∼ 0.95 followed by a higher rate lasting ∼ 0.2 in phase. It is instead flatter for E > 3 keV (Figure 2). The faint phase (pulse minimum) is slightly flatter above 3 keV, while it shows a smooth decline below it. The PF varies from 75 per cent in the 0.3–1 keV band to 45 per cent in the 5–12 keV band (Table 1). The modulation reveals the typical bright and faint phases seen in the polars, which are produced by the accretion flow above the main (or upper) pole which comes into (bright phase) and out of (faint phase) view if the magnetic and rotation axes are offset by an angle β defined as the magnetic colatitude, and shifted in azimuth (ψ) (see Cropper 1988). The non-zero count rate during the faint phase could suggest either that the accreting upper pole does not completely disappear behind the WD limb or that a second emitting region is present. The length of the faint phase can be used to restrict the range of values of the binary inclination i and colatitude β of the main pole (Cropper 1990). The lack of eclipses implies ≤ 75°. These give 41° ≤ β ≤ 87° for 10° ≤ i ≤ 75°. The energy dependence of the dip and pre-dip maximum is reminiscent of absorption from the accretion stream at the threading.
Table 2. Timing properties of the source sample. Uncertainties are at 1σ confidence level. From left to right: $P_X^\Omega$ (X-ray spin period); $P_{X,side}^\Omega$ (X-ray sidebands); $P_{X,lc}^\Omega$ (orbital period derived from X-ray light curve fitting); $A_{X}^\omega/A_{X,side}^\omega$ (spin to sideband X-ray amplitude ratio); $P_{opt}^\omega$ (optical spin period from OM); $P_{opt}^{\omega,lc}$ (optical orbital period as derived from OM or ground-based observations); $P_{opt}^{\omega,lc}$ (adopted orbital period in this work with its reference in parenthesis).

| Source  | $P_X^\Omega$ s | $P_{X,side}^\Omega$ h | $P_{X,lc}^\Omega$ h | $A_{X}^\omega/A_{X,side}^\omega$ | $P_{opt}^\omega$ s | $P_{opt}^{\omega,lc}$ h |
|---------|----------------|------------------------|---------------------|-------------------------------|------------------|----------------------|
| J0706   | 6135 ± 5       | -                      | -                   | -                             | -                | -                    |
| J0746   | -              | -                      | -                   | -                             | -                | -                    |
| J0801   | 1310.9 ± 1.5   | -                      | -                   | 1036.3 ± 0.9                  | -                | -                    |
| J0927   | 1033.5 ± 0.5   | 5.25 ± 0.45            | 5.15 ± 0.10         | 1030.6 ± 0.9                 | -                | -                    |
| J0958   | 296.22 ± 0.05  | -                      | -                   | -                            | -                | -                    |
| J1701   | 1859±3         | -                      | -                   | 1858.67 ± 0.02²               | -                | -                    |
| J2113   | 1265.6±4.5     | 4.46 ± 0.10            | 4.02±0.10           | 1.1                          | -                | -                    |

* Short-term variability with timescale of about 2700 s is present in the first half of the observation only.
* Period derived from OM data ($\sim 2\Omega_P$).
* Spin period derived from AAVSO V-band photometry. From OM we get 1857 ± 6 s.
* Orbital period derived from multi-site optical photometry.

[1] Halpern & Thorstensen 2015; [2] Thorstensen & Halpern 2013; [3] This work.

Table 3. Pulsed fraction vs energy. Results refer to the fundamental frequency (ω) (Table 2, column 2), n is the number of sinusoids used to fit the data. Uncertainties are at 1σ confidence level.

| Source     | Pulsed Fraction | n |
|------------|-----------------|---|
| J0706      | 64%             | 3 |
| J0927      | 46%             | 3 |
| J0958      | 2%              | 2 |
| J0801      | 1%              | 2 |
| J1701      | 3%              | 1 |
| J2113      | 1%              | 1 |

The PF is calculated using the more accurate optical spectroscopy period (5026.36 s) from Halpern & Thorstensen 2015.

For E = 0.3 – 1 keV only, the first harmonic has the highest PF (69 ± 4 per cent).

Results refer to the first 26 ks of the pointing only. The last 12 ks are removed because of high background contamination.

Results refer to the second half of the pointing only, where the background level is low.

4.1.2 Spectral analysis

While a simple optically thin plasma with kT = 11.5 ± 0.7 keV and $\Lambda_X = 0.4 ± 0.1$ absorbed by only a partial covering column well fit the average broad-band spectrum ($\chi^2 = 1.06$, 336 d.o.f.), a multi-temperature plasma CEMELK with $\alpha = 1.0$ (fixed), kT$_{max} = 46 ± 4$ keV, and with the same underabundance gives the same $\chi^2$ and alleviates a problem of the inter-calibration constant between the EPIC and BAT spectra. Despite this, the partial covering parameters are less constrained (Table 2 and Figure 3). The source spectrum does not require either a soft blackbody component or a Gaussian for the 6.4 keV line. Furthermore, only a 3σ upper limit to the hydrogen column density of the total absorber is derived, a factor $\sim 30$ lower than the total value in the source direction [Kalberla et al. 2005]. This suggests that the source distance is small as also indicated by its large proper motion [Skinner, Thorstensen & Lépine 2014; Halpern & Thorstensen 2015]. To independently verify that the post-shock plasma is not isothermal we performed a joint EPIC+RGS fit using the one-T model with the temperature, abundance, and absorbing partial covering column parameters fixed to the values obtained in the EPIC+INTEGRAL/IBIS fit. The new fit clearly shows an excess at $\sim 0.57$ keV, and probably also around 0.65 keV. Allowing for an additional simple absorber and narrow Gaussians, we measure a line at 0.573 keV ($\sim 21.647 \pm 0.0001$), an equivalent width EW= 15 ± 5 eV at 90 per cent confidence, and less robustly a probable line at 0.65 keV. These are identified as the He-like triplet of OVII and H-like line of OVIII, neither of which is in the best-fit 1-T model. These lines indicate the presence of plasma at $\sim 0.4 - 0.6$ keV, likely forming at the base of the post-shock region. We conclude that the shock plasma is indeed not isothermal and consider the CEMELK model the best description of the data. Although the PSR model is not applicable to polars, J0706 is likely a low-field Polar (Sect. 4.1.3) and thus cyclotron cooling should not strongly affect the PSR structure. With this note of caution, we consider the derived WD mass from PSR model a lower limit which results: $M_{WD} \geq 0.79 M_\odot$ (Table 5).

Both parameters of the multi-temperature plasma decrease at orbital minimum as expected in a polar system, where the main ac-
J0706 was identified in the nIR at $m_{\text{nIR}}$ (Table 6). Assess whether this contribution is important at the orbital minimum absorption component is poorly constrained and we are unable tocretion spot comes in and out of view along the orbital cycle. The absorption component is poorly constrained and we are unable to assess whether this contribution is important at the orbital minimum (Table 6).

4.1.3 A hard X-ray and low-B field polar

J0706 was identified in the nIR at $K_s=14.54$ mag (Skinner, Thorstensen & Lépine 2014). It also appears in the 2MASS catalogue as 2MASS J07064892+0324472 with $J=15.585\pm0.065$, $H=14.843$ and $K=14.541\pm0.105$ mag. It is further detected in the mid-IR with the Wide-field Infrared Survey Explorer (WISE) (Wright et al. 2010) as WISE J07064895+0324469 in the W1 (3.35 \mu m), W2 (4.6 \mu m), and W3 (11.6 \mu m) bands: $W1=13.228\pm0.024$, $W2=12.563\pm0.026$ and $W3=10.751\pm0.116$ mag. The upper limit to the column density of a total absorber indicates that extinction is negligible and translate to $A_V \lesssim 0.05$ (Güver & Özel 2009). The 2MASS colour J-K=1.04 \pm 0.12 is consistent with a late type (M5–M6 V) donor star (Straižys & Lazauskaite 2009). A M5.3 V spectral type is also expected for a donor in a 1.7 h binary (Smith & Dhillon 1998). However, though WISE and 2MASS data are not contemporaneous, the K-W1, W1-W2, and W2-W3 colours are much redder for such spectral type (Pecaut & Mamajek 2013), indicating a mid-IR excess. A number of polars studied in the nIR and mid-IR have also shown extreme colours in the WISE bands (W2-W3$\lesssim 1$; Harrison et al. 2013; Bernardini et al. 2014; Harrison & Campbell 2015), ascribed to cyclotron radiation with the fundamental harmonic falling in the W3 band (Harrison & Campbell 2015). The IR excess in the case of cyclotron origin is also expected to be variable at the orbital-rotational period, but the single exposure WISE data are too sparse to reveal a modulation. The position of J0706 in the mid-IR colour-colour diagram (W1-W2;W2-W3, see Figure 1 in Harrison & Campbell 2015) falls in a region consistent with the presence of a cyclotron fundamental in the W3 band. This suggests a moderately low magnetic field ($\lesssim 7 - 10 \times 10^5$ G). We then use 2MASS K-band magnitude to estimate the distance. Adopting a M5–M5.6 V donor with $M_K = 8.3 - 8.6$ (Knigge...
Figure 2. X-ray (PN) pulse profiles at different energy intervals. Energy increases from top to bottom. Two pulse cycles are shown for plotting purposes. The folding period is also reported on the top left of each figure. The reference folding time for each source is the integer of the observation starting time (Table 1) with the exception of J0706, where is MJD=56681.8996 (Halpern & Thorstensen 2015). For all sources, the X-ray PF decreases as the energy increases (Table 3). Optical pulse profiles are also shown when the source displays optical pulses. Since the optical pulse is less intense than the X-ray pulse, it is plotted on a different scale.
New magnetic CVs observed with XMM-Newton

Figure 3. Broadband unfolded spectra. Post fit residuals are shown in the lower panels. Black points are XMM-Newton/PN data (0.3–10 keV), blue points are Swift/BAT data (15–80 keV) or INTEGRAL/IBIS data (20–100 keV) for J0801 only. The fit is made simultaneously on all EPIC cameras, but for sake of readability, we only show PN data. The dotted lines mark individual model components, while the solid line is the composite model.
Table 4. Model parameters of the best fit models to the averaged broad-band spectra of the sources under study. The absorbed 0.3–10 keV and unabsorbed bolometric (0.01–200 keV) fluxes are reported in the last two columns. Uncertainties are at 1σ confidence level.

| Source | mod. | N_Hp | N_Hp,1023 | cvf | N HI,p,1022 | cvf | kT_BB | kT_e | kT_h | n_H,10^20 | n_c | n_h,10^3 | A_Z | EW | F_0.3–10 | F_X,bol |
|--------|------|------|----------|-----|------------|-----|------|------|------|---------|-----|---------|-----|----|----------|--------|
| J0706  | cemek & 1.05/336 | ≤ 0.01 | 87.5 ± 33 | 33.15 | - | - | - | - | 11.0 ± 0.4 | - | 0.41 | 0.20 | 6.3 | ∼ 1.9 |
| J0746  | mek & 1.10/125 | ≤ 0.03 | 7.4(7) | - | - | - | - | 0.21 | - | - | 0.46 | ∼ 0.06 |
| J0746  | A:mek & 1.33/53 | 0.06(2) | 48.66 | - | - | - | - | - | 4.65 | - | 1 (fix) | - | 8.2 | ∼ 2.1 |
| J0746  | B:mek & 0.89/52 | 2.2 ± 1 | - | - | - | - | - | - | 5.33 | - | 1 (fix) | - | - | ∼ 2.0 |
| J0801  | brem-pow & 1.33/251 | ≤ 0.01 | 4.7(4) | 84.1 | 33.15 | 76(2) | - | - | 11.0 ± 0.9 | - | - | - | 1.04 | 2.7 | ∼ 4.8 |
| J0927  | mek & 1.62/320 | 0.06(1) | 16.5(19) | 79(3) | - | 36(14) | 0.07 ± 0.04 | - | 0.84 ± 0.11/14 | 0.14 | - | 4.9 | ∼ 2.2 |
| J0958  | BB+mek & 1.08/294 | 0.26(4) | 65(1) | - | - | - | - | 5.3(1) | 6.0 ± 0.2 | ∼ 54 | 4.3 ± 0.9 | 0.9 ± 0.3 | 5.6 | 2.3 | 0.13 | 8.0 | ∼ 41 |
| J1701  | BB+2mek & 1.10/566 | 0.76(4) | 3.7(5) | 73(2) | 17(5) | 38(6) | - | - | 4.0(5) | 31(7) | - | 2.6 | 6.3 | 1.8 | 0.07 | 9.3 | ∼ 2.6 |

Table 5. WD masses (M_{WD}), distances (d), and mass accretion rates (Ṁ) of the sources in the sample.

| Source | M_{WD} | d | M | Σ |
|--------|--------|---|---|---|
| J0706  | ≥ 0.79 | 230 | ~ 1.3 × 10^-11 | |
| J0801  | 1.18 ± 0.10 | 250 | ~ 1.5 × 10^-11 | |
| J0927  | 0.58 ± 0.11 | ≤ 670 | ~ 2.2 × 10^-10 | |
| J0958  | 0.74 ± 0.11 | 720–1100 | ~ 1.8 – 4.2 × 10^-10 | |
| J1701  | 1.16 ± 0.12 | 1000 | ~ 2 × 10^-9 | |
| J2113  | 0.81 ± 0.16 | > 750 | ~ 1.7 × 10^-10 | |

T & A Blackbody normalization defined as L_{39}/D_{10}^2, where L_{39} is the source luminosity in units of 10^{39} erg/s and D_{10} is the distance to the source in units of 10 kpc.

* Multi-temperature power-law index α fixed to 1.

* 3σ upper limit (results refer to a model without this component).

* Fit results for EPIC data only.

* Fit results for XRT plus BAT data.

* Power law photon index and normalization.

* BAT inter-calibration constant is 0.50 ± 0.07 for J1701, and 0.60 ± 0.12 for J2113.

* 3σ lower limit.

The lack of a soft X-ray blackbody component is not surprising given the recent discovery of an increasing number of polars not displaying such soft X-ray emission (Ramsay & Cropper 2004). A shift in the EUV or FUV bands due to large footprints may be possible. However, as pointed out by Ramsay et al. (2009), there is no obvious explanation for why these hard polars should have larger accretion areas, since their orbital period and magnetic field strengths are not so different from other polars. The hard X-ray detection of polars also poses the question of whether the few (now 11) that are hard X-ray selected possess lower magnetic fields and/or more massive WDs. J0706 appears to show both properties.
Table 6. Spectral parameters at spin max and min. Other parameters are fixed to their average spectrum best-fit values. Uncertainties are at 1σ confidence level.

| source         | N_{H1}\perp 10^{22} cm^{-2} | cvf % | N_{H1}\perp 2 \times 10^{22} cm^{-2} | cvf % | kT_{BB} keV | kT_{c} keV | kT_{b} keV | n_{BB} \times 10^{-3} | n_{c} \times 10^{-3} | n_{b} \times 10^{-3} | EW keV | F_{0.3–10} \times 10^{-12} erg cm^{-2} s^{-1} | χ^2/dof |
|----------------|-----------------------------|-------|-------------------------------------|-------|--------------|------------|------------|-----------------|----------------|----------------|--------|-------------------------------------------|---------|
| J0706          |                             |       |                                     |       |              |            |            |                 |                |                |        |                                           |         |
| max (φ=0.70–1.20) | -                           | -     | 6.5±^{10}_4 22(6) |      | -            | -          | 45.8 (6x)  | -               | 12.9±0.1      | -             | 9.9(4) | 0.85/105                                  |         |
| min (φ=0.30–0.60) | -                           | -     | 2.9 ±^{10}_7 79±20 |      | -            | -          | 5.1±^{3.9}_1.5 | -               | 5.2±2         | -             | 1.7±^{0.1}_0.7 | 1.26/24     |         |
| J0801          |                             |       |                                     |       |              |            |            |                 |                |                |        |                                           |         |
| max (φ = 0.10 – 0.40) | 4.6(7) | 72(7) | -                                    | -     | 1.05(8)     | 0.8(3)c   | -          | 2.3(5)         | 0.10(4)c      | < 0.3         | 3.1(1) | 1.09/137                                  |         |
| min (φ = 0.50 – 0.90) | 5.2±^{1.6}_1.7 | 41(25) | -                                    | -     | 0.8(4)      | 1.4(3)c   | -          | 0.5(1)         | 0.3(1)c        | 0.3(1)       | 2.4(2) | 1.13/141                                  |         |
| J0927          |                             |       |                                     |       |              |            |            |                 |                |                |        |                                           |         |
| max (φ = 0.71 – 0.85) | 6.2(17) | 92(3) | 32±^{1.7}_4 76(7) |      | -            | -          | 17(5)     | -               | 7.8(5)        | 0.16(3)      | 6.6(2) | 1.15/160                                  |         |
| min (φ = 0.20 – 0.55) | - | - | 17.5(27) 61(3) | 0.078(4) | - | 20±^{2}_4 0.09(2) | - | 4.1(2) | 0.21(4) | 5.2(2) | 1.17/157 |         |
| J0958          |                             |       |                                     |       |              |            |            |                 |                |                |        |                                           |         |
| max (φ = 0.75 – 0.99) | - | - | 15.0(25) 69(2) | 0.067(9) | - | 36.27 (fix) 0.07(4) | - | 3.0(2) | 0.37(8) | 3.6(1) | 1.17/59 |         |
| J1701          |                             |       |                                     |       |              |            |            |                 |                |                |        |                                           |         |
| max (φ = 0.35 – 0.65) | 7.4(7) | 52(2) | -                                    | -     | 0.053(2) 6.0±^{2.3}_1.4 79.9 (fix)c | 5.1±^{1.6}_1.2 0.90(3) | 6.6(4) | 0.11(2) | 9.6(1) | 1.16/271 |         |
| min (φ = 0.90 – 1.20) | 10.2(7) | 82(1) | -                                    | -     | 0.048(7) 7.5(17) 79.9 (fix)c | 8.6±^{0.9}_0.3 0.96(3) | 4.8(4) | 0.18(2) | 6.3(1) | 1.11/208 |         |
| J2113          |                             |       |                                     |       |              |            |            |                 |                |                |        |                                           |         |
| max (φ = 0.60 – 0.90) | 3.1(6) | 67(4) | 15(4) 42(8) | - | 4(2) | 28(6)     | -          | 2.2(5) | 7.0(6) | 0.07(2) | 10.1(3) | 0.88/256 |         |
| min (φ = 0.05 – 0.30) | 3.9(7) | 78(4) | 20±^{1.5}_0 32(10) | - | 5(2) | ≥ 22b     | -          | 3.1(4) | 5.5(10) | 0.09(2) | 8.5(4) | 0.82/245 |         |

a Fixed to the average spectrum best-fit value.

b 3σ lower limit.

c Power law photon index and normalization.

4.2 Swift J0746.3-1608

J0746 was identified as a CV independently by Thorstensen & Halpern (2013), where it figures as Swift J0746-1611, and Parisi et al. (2014), and proposed as either a novallike system or a magnetic system because of its optical spectral characteristics. From the late-type secondary absorption lines Thorstensen & Halpern (2013) derived a long orbital period of 9.38 h and a distance of 900±190 pc.

4.2.1 Timing analysis

The X-ray lightcurve shows a faint source (~ 0.14 c/s, in the PN). In the first half of the pointing there are at least five flare-like events of variable amplitude (up to a factor of 6) with timescale of about 2700 s (Figure 3), but these do not appear to be periodic. The HR vs time are constant within uncertainty. The optical (B-band) light curve (Figure 4), where no flares are detected, shows instead a modulation with amplitude Δ B = 0.10 mag. Although covered only for two cycles, we estimate a period of 5.03±0.10 h, about half the spectroscopic orbital period found by Thorstensen & Halpern (2013). These authors did not detect any modulation in their photometry of Jan. 2013, but instead an erratic variability. This indicates that this source is variable on a long-term timescale (yrs).

Indeed Thorstensen & Halpern (2013) presented the Swift-XRT light curve of J0746 covering the period between 2009 and 2011. The source is highly variable with count rate changing up to a factor of ~ 20 on timescale of a few hours. Two additional pointings in Jun. 2013 and Aug. 2015 showed the source had faded to a count rate of ~0.05 c/s from a maximum of about ~ 0.7 c/s during 2009–2011. It then appears that a substantial change of the X-ray fluxes occurred after 2011. We then inspected the Swift-UVOT photometry acquired since 2009, in the U, UVW1 and UVW2 filters. The source also faded in the UV and U bands after June 2011, by ~1.3 and ~1.0 mag, respectively. We further inspected the optical long-term history using B-band photometric measures from USNO-A2 catalogue (B=13.4 mag, in 1953), USNO-B1 catalogue (B1=14.5 and B2=14.7 mag, in 1971), the Guide Star Catalogue (GSC 2.2) (B=14.55 ± 0.41 mag in 1984), and the APASS catalogue (B=15.02 ± 0.02 mag in Jan. 2011). These, compared with the OM photometry (B=16.33 ± 0.03 mag), further confirm the fading at optical wavelengths. The double humped orbital modulation in the B band observed with the OM could be due to ellipsoidal modulation of the donor star filling its Roche lobe. The two minima of the light curve correspond to the inferior and superior conjunction of the secondary, according to the spectroscopic ephemeris of Thorstensen & Halpern (2013). The lack of multi-band photometry does not allow to further investigate the origin of the optical modulation and so to confirm this hypothesis.

8 The last quarter of the XMM-Newton pointing was removed from the analysis because it was affected by high background level.
about half the orbital period, while the X-ray light curve shows flaring in the first part of the pointing. Right: Broadband unfolded spectrum of J0746. Post fit residuals are shown in the lower panel. In black are Swift/XRT data (0.3–10 keV), in blue Swift/BAT data (15–50 keV), and in red XMM-Newton/PN (0.3–10 keV) data. The fit uses model A in Table I and it is made separately on Swift (XRT+BAT) and XMM-Newton (EPIC) data. The spectra are plotted together to highlight the source flux variability.

4.2.2 Spectral analysis

Due to the remarkable long-term X-ray variability, the EPIC spectra were fitted without the high-energy coverage from the Swift-BAT instrument, which would require an unfeasible inter-calibration constant as high as 100. This suggests that when observed by XMM-Newton the source was much fainter than its average over many years. The spectrum (Table I and Figure B) is satisfactorily fitted with a MEKAL with kT = 7.4 ± 0.7 keV and A_Z = 2.1 ± 0.4 (χ^2 = 1.1, 125 d.o.f.). Similar χ^2 is also obtained using a simple power law (with photon index 1.70 ± 0.05), but an excess results at the iron complex. This makes us prefer the former model. The absorption is very low, with a 5σ upper limit of N_H ≤ 3×10^{20} cm^{-2}, at least a factor ~10 lower than the total galactic column density in the direction of the source that lies in the dust lane and consistent with the optical extinction by Thorstensen & Halpern (2013). The absorbed 0.3–10 keV flux is low (4.6×10^{-13} erg cm^{-2} s^{-1}) indicating a very low mass accretion rate and consequently a negligible intrinsic absorption. Furthermore, the lack of a fluorescent line at 6.4 keV is also consistent with such low state, where reflection from cool material is negligible. No significant spectral change, except for the normalization of the MEKAL, is found extracting the in-flare and out-flare spectra, as also indicated by the constant HR.

Given the source long-term X-ray variability, we analysed the average XRT spectrum which covers the higher state observed between Aug. 2009–Jun. 2011 (IDs: 38960, 40698, 41163 and 90159). We fitted the broadband XRT+BAT spectrum adopting a thermal component, since a power law fails to account for the BAT data. We first used model A, a MEKAL (with the abundance fixed to Solar) multiplied by PHABS obtaining kT= 39±5 keV and N_H = 6 ± 2 × 10^{20} cm^{-2} (χ^2 = 1.33, 53 d.o.f.). An improved fit is found using model B, where a partial covering absorber is used in place of PHABS (when using both, the latter is totally unconstrained) and gives kT= 19±5 keV, N_{H,pc}= 2.2 ±0.2 × 10^{22} cm^{-2}, and cvf=48 ± 6 per cent (χ^2 = 0.89, 52 d.o.f.). Here we note that the former fit gives a column density in line with the estimated extinction (Thorstensen & Halpern 2013). We notice that for both models the BAT inter-calibration constant is now consistent with unity, within uncertainty. The XRT 0.3–10 keV flux is ~ 8.3 × 8.9 × 10^{-12} erg cm^{-2} s^{-1}, a factor ~17 larger than in the XMM-Newton observation (Table I and Figure B). If instead compared with the maximum flux recorded by XRT, the source in April 2016 is a factor of ~ 70 fainter.

4.2.3 An atypical low accretion rate CV or a LMXB?

J0746 faded after 2011, and in April 2016 it was at its lowest level ever observed. At the distance of 900 pc, the bolometric X-ray luminosities in the high and low states are 2.0×10^{33} erg s^{-1} and 5.8 × 10^{31} erg s^{-1}, respectively. Both values, for a WD mass in the range 0.6–0.8 M_{⊙} would give accretion rates of ~ 2.0 – 3.4 × 10^{-10} M_{⊙} yr^{-1} and ~ 0.6 – 1.1 × 10^{-11} M_{⊙} yr^{-1}, respectively. These fall too short (at least 2–3 orders of magnitudes) with respect to those of systems above the gap (McDermott & Taam 1989; Howell, Nelson & Rappaport 2001), unless evolved donors are taken into account (Goliash & Nelson 2015).

The short and long-term X-ray and optical variabilities observed in J0746 are difficult to reconcile with a long-period nova-like CV that is expected to have a large accretion disc that acts as a reservoir. Furthermore the lack of periodic pulsations (with the caveat of the low S/N) in the typical range of MCVs, also rules out the possibility that this systems harbours a magnetic WD. The peculiar flaring activity, the low luminosity level in both high and low states poses the question on whether J0746 is indeed a CV or a low-mass X-ray binary (LMXB). X-ray variability and luminosities down to 10^{31} – 10^{33} erg s^{-1} are observed in transient LMXBs (with both neutron star or black hole primaries) during quiescence (e.g. Hynes et al. 2004; Degenaar & Wijnands 2012; Bernardini et al. 2013a; Bernardini & Cackett 2014). Those harbouring neutron stars (NS) show X-ray spectra generally revealing the optically thick thermal emission from the NS atmosphere at several tens of eV and/or a power law hard tail ascribed to non-thermal emission processes possibly related to the magnetic field of the NS (see e.g. Degenaar & Wijnands 2011, 2012). Black hole
LMXBs, so far discovered through their strong outbursts except for a recent detection by Tetarenko et al. (2016), show hard X-ray power laws during quiescence (with power law index very close to 2) but is 2.9 arcmin away from J0746. The Swift long-term monitoring does not give evidence that J0746 has undergone an outburst over the last 7 years and its spectrum, especially during the high state, seems to be thermal (and not a simple power law). On the other hand, the observed behaviour in J0746 may be reminiscent of the sub-luminous states of two LMXBs, PSR J1023+0038 and XSS J12270-4859, harbouring millisecond pulsars (MSPs) that initially were wrongly classified as CVs (see Archibald et al. 2004, de Martino et al. 2010). These pulsars were observed to transit from LMXB to MSP radio phases and vice versa and consequently defined as transitional MSPs (tMSPs; Archibald et al. 2004, de Martino et al. 2010, 2013, Bassa et al. 2014, de Martino et al. 2014, 2015; Bogdanov et al. 2015). During the LMXB state, they show peculiar high (persistent emission) and low (dips) modes besides erratic flaring activity, with msec pulses detected during the high mode only (Archibald et al. 2013, Papitto et al. 2015). In J0746 dipping behaviour is not observed, but we are unable to search for pulsations in the 1–10 msec range, due to the temporal resolution of the EPIC camera. Furthermore, differently from J0746, the X-ray spectra of tMSPs are featureless and described with a simple power law.

Additionally, at the X-ray levels observed in J0746 and drawing similarities with two tMSPs, a detection of a Gamma-ray source by Fermi-LAT would have been possible. However, we inspected possible Gamma-ray positional associations of J0746 and found that the only close Fermi-LAT source is 3FGL J0748.0-1639, but it is 37.6 arcmins away. The 4th Fermi-LAT catalogue (Acero et al. 2015) gives a 95\% error ellipse of 0.12 deg×0.14 deg, excluding a positional association with J0746. Furthermore, this source has a different Gamma-ray spectrum than those of the tMSPs. We also inspected radio catalogues through the Heasarc website and found no radio source consistent with the position of J0746\(^9\). In summary, the lack of positional Gamma-ray or radio association does not support a MSP classification.

While a quiescent LMXB in a prolonged (years) low state could not be excluded, the thermal spectrum of this source may favour an atypical low luminosity CV. High and low states seen in J0746 could be explained if the donor is not completely filling its Roche-lobe allowing for fast changes in the accretion rate as well as accounting for the low state after 2011. CVs entering extended low states are seen in the VY ScI star subclass, but they have shorter orbital periods (typically 3–4 h). This system poses the same questions regarding the true nature of the low-luminosity CV, V405 Peg, which is however just at the upper end of the VY ScI stars orbital periods (P_{orb} = 4.2 h; Schwinge et al. 2014). The other type of CVs undergoing high and low states on timescales of years are the polars, but our data do not support a magnetic nature. In particular at the long orbital period of J0746, no Polars are known except for V1309 Ori (P_{orb} = 8.0 h, B = 4.5 × 10^7 G), which however is a blobby-accretor and displays one of the most extreme soft-to-hard flux ratios (de Martino et al. 1998, Schwarz et al. 2005). J0746 does not share any similarity with this system. On the other end, the optical spectra acquired in 2010 (Thorstensen & Halberi 2013, Parisi et al. 2014) show intense emission lines of Balmer series and He II, with H_β and He II(4686 Å) equivalent width ratios similar to those observed in polars and novalikes and much larger than those observed in LMXBs (van Paradijs & Verbunt 1984).

In conclusion there are no strong indications favouring either an LMXB or a typical long-period CV, but if its X-ray spectrum is indeed thermal as it seems more likely, we suggest it could be a CV accreting at an unusually low rate for its long orbital period. This is not in disagreement with the recent results by Pala et al. (2017) who also found several long-period CVs accreting at unexpectedly low rates. Both an X-ray monitoring and a new long X-ray observation of J0746 in a higher state are desirable to shed light into the true nature of this peculiar source.

4.3 PBC J0801.2-4625

J0801, =1RXS J080114.6-462324 in Masetti et al. (2010), was identified by those authors as a CV and tentatively suggested as magnetic. It was observed in April 2016 by Swift-XRT due to a possible, though uncertain, association with the fast soft X-ray transient MAXI J0758-456 (Masumitsu et al. 2016, Kennea et al. 2016).

4.3.1 Timing analysis

The X-ray and V-band light curves display clear short term variability. The power spectra in both bands show a strong, isolated, peak at ~ 7.6 × 10^{-3} Hz. We measure a period of 1310.9 ± 1.5 s in the X-ray band and 1306.3 ± 0.9 s in the V-band, respectively. This suggests that the spin period of the accreting object. The 0.3–12 keV and V-band pulses are broadly in phase and have similar PF (15.3 ± 1.5 per cent and 13.8 ± 0.3 per cent, respectively). The X-ray PF slightly decreases with energy, from 20 ± 2 per cent in the softer to 9 ± 6 per cent in the harder band (Table 4 and Figure 4).

Given the purported association to the transient detected by MAXI a compact star spinning at 1300 s could be either a NS or a WD. However, slow NS rotators at the rate observed in J0801 are found only in high-mass X-ray binaries, and in the few known symbiotic X-ray binaries and none detected in LMXBs (Patruno & Watts 2012). The optical spectrum (Masetti et al. 2010) clearly disfavors an early type counterpart as well as a K–M giant. Furthermore, the presence of the pulsation in both the X-ray and optical bands is typically observed in CVs being the optical spin modulation produced in the magnetically confined accretion flow onto the WD poles. The more energetic LMXBs do not generally show optical spin pulsations. Therefore, the X-ray and optical modulations in J0801 strongly suggest a MCV of the IP type. The presence of only the spin period further implies that that accretion occurs via a disc (Rosen, Mason & Cordova 1988).

4.3.2 Spectral analysis

The EPIC spectra of J0801 are not easy to reconcile with the typical X-ray spectra of magnetic CVs. This is the only source of the sample for which a model based on a thermal continuum do not provide the best fit in terms of χ². The combined XMM-Newton and INTEGRAL broad-band spectrum can instead be described by a simple model (Table 2 and Figure 3) consisting of \( kT_{e} = 0.98 \pm 0.06 \) keV and a power law with photon index 1.0 ± 0.1 (dominating for \( E \gtrsim 3 \) keV) plus a Gaussian at 6.4 keV with EW= 100 ± 40 eV, all multiplied by PCFABS with \( N_{H,p} = 4.0 \pm 0.6 \times 10^{22} \) cm^{-2}, and cvf=0.61±6 per cent. Only a
3σ upper limit to the hydrogen column density of the total absorber is obtained ($N_{\rm H} \lesssim 1.6 \times 10^{20} \text{ cm}^{-2}$), a factor of about 15 lower than the total value in the source direction. The hard component is not compatible with a second TREMSS since an unrealistic temperature of 200 keV is obtained, even including the effect of reflection from neutral material (REFL in XSPEC).

On top of its peculiar spectrum, we also note that $\chi^2$ is slightly high (1.33, 252 d.o.f.), and we found that this is in part due to post-fit residual features at low energies ($\lesssim 3 \text{ keV}$). Due to the low S/N, they could be modeled with either absorption or emission lines (we note that in the latter case a MEKAL lines (we note that in the latter case a MEKAL spectrum gives a feature at 200 keV is obtained, even including the effect of reflection from neutral material (REFL in XSPEC)).

Due to these complexities, the PSR model has been applied to the broad-band spectrum above 3 keV from which a massive WD ($M_{\text{WD}}=1.18 \pm 0.10 M_{\odot}$) is obtained (Table 5).

Only the normalization of the thermal component increases by a factor of $\sim 5$ at pulse maximum, while all other parameters are constant within uncertainty (Table 6). The spin modulation then seems mainly due to visibility changes of the post-shock region, rather than to absorption effects.

### 4.3.3 A low accretion rate IP?

Due to the source faintness during the XMM-Newton pointing and the purported association with the fast MAXI transient source, all available archival Swift-XRT observations (obsid 34515 in 2007 and 262347 in 2016) were inspected for long-term changes. Similar fluxes are measured during these observations, indicating a likely intrinsically faint source. This does not exclude the possible association with the bright (1.4 Crab) fast-flaring source, and thus that J0801 could be a LMXB in deep quiescence. However, while the X-ray spectrum is atypical for a CV, the presence of pulses in both X-ray and optical bands strongly supports J0801 harbouring a magnetic WD. Furthermore, the optical spectrum by Masetti et al. (2010) acquired in 2009 displays strong emission lines (Balmer, He I and He II) with EW ratio of H$_{\alpha}$ and He II close to those observed in magnetic CVs and much larger than those of LMXBs (Van Paradijs & Verbunt 1984).

J0801 is detected in the nIR as 2MASS J08011702-4623274, with $K=14.442 \pm 0.041$, $H=14.032 \pm 0.050$, and $K=13.774 \pm 0.058$ mag, as well as in the midIR as WISE J080116.96-462327.5 with $W1=13.307 \pm 0.025$, $W2=13.153 \pm 0.027$, and $W3=13.401 \pm 0.021$ mag. As shown in Sect. 4.3.2, extinction is negligible. The nIR colour J-H=0.41 $\pm$ 0.06 suggests a K-type donor star, but those at longer wavelengths, $H-K=0.28 \pm 0.08$ and $W1-W2=0.15 \pm 0.04$ are instead both compatible with a M4 V star (Bijl et al. 2008, Straizys & Lazauskaite 2009, Pecaut & Mamajek 2013). This implies that accretion affects the emission above 1.2 $\mu$m. For an assumed M4 V donor a distance of 250 pc is obtained using the observed and absolute K-band magnitudes ($M_{K}=6.76$) (Knigge 2006). Such small distance would imply the closest LMXB ever known, especially if associated to the fast MAXI transient source. All this makes the magnetic CV interpretation more plausible.

The lack of multi-colour photometry does not allow to infer a possible contribution of reprocessed emission at UV/optical wavelengths as would be expected from the detection of pulsations in the V-band (see also Mukai, Ishida & Osborn 1994). However, given the small optical pulse amplitude ($\sim 14$ per cent), reprocess should not be important. We then estimate the accretion luminosity adopting a distance of 250 pc as: $L_{\text{acc}} \sim L_{X,\text{bol}} = 3.6 \times 10^{32} \text{ erg s}^{-1}$. Using the inferred WD mass (Table 5) a mass accretion rate $\dot{M} \sim 1.5 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$ is derived. This value is close to that of a system loosing angular momentum through gravitational radiation below the 2–3 h orbital period $P_{\text{orb}}$. J0801 may resemble those short period IPs, like HT Cam (de Martino et al. 2005), with a spin pulse not affected by absorption and accreting at a low rate. Although the binary period cannot be measured with the present data, if the donor spectral type is indeed M4 V, J0801 is expected to have $P_{\text{orb}} \sim 2–3$ h (Knigge 2006), quite consistent with the above arguments. Time-resolved optical spectroscopy is needed to assess whether J0801 is indeed a short orbital period system. Also, the peculiar X-ray spectrum requires a more detailed analysis with higher quality X-ray spectroscopy to classify it as an ‘ironclad’ IP.

### 4.4 Swift J0927.7-6945

J0927 was identified from optical spectroscopic follow-ups by Parisi et al. (2014), as a CV, likely of the magnetic type. It appears as PBC J0927.8-6945 in their work.

#### 4.4.1 Timing analysis

The X-ray and optical light curves display short-term and long-term variability (Figure 1). The X-ray power spectrum shows a strong peak at $\sim 9.7 \times 10^{-4}$ Hz and weaker ones at twice and three times this frequency. Power is also detected close to the main peak at $\sim 9.2 \times 10^{-4}$ Hz. We measure $P_{1}=1033.54 \pm 0.51$ s and $P_{2}=1093.4 \pm 6.5$ s, with an amplitude ratio $A_{2}^{2}/A_{1}^{2} \sim 2.5$. The shorter period is then identified as the WD spin period and the other as the beat ($\omega - \Omega$). The power spectrum also shows substantial power at low frequencies. The lightcurve indeed displays almost two cycles of a possible periodic modulation, which could be the orbital period. It is asymmetric and we use two sinusoid functions (fundamental and harmonic) to determine its period: $P_{1}=5.15 \pm 0.10$ h. This is consistent with that obtained from the beat frequency ($\omega - \Omega$): $P_{2}^{\text{side}}=5.25 \pm 0.45$ h. Thus, J0927 is undoubtedly an IP. The presence of a dominant spin pulsation in the X-ray band implies that it mainly accretes through a disc, although a non negligible fraction ($\sim 40$ per cent) of the accretion flow overpasses the disc and impacts directly onto the WD poles. The optical B band light curve instead shows evidence of the spin period only ($P_{\text{opt}}=1030.6 \pm 0.9$ s), together with a longer timescale (hours) non periodic variability.

The presence of harmonics up to the second implies a structured X-ray spin pulse profile (Figure 2). The two main peaks giving rise to the fundamental and first harmonic are separated by 0.4 in phase. The PF decreases with increasing energy (Table 6), but the first harmonic almost dominates the 0.3–1 keV energy range (PF up to $\sim 70$ per cent), and loses power as the energy increases. This may indicate the presence of two emitting poles with the lower one dominating at low energies. The optical pulse profile is instead almost sinusoidal ($\Delta B \sim 0.1$ mag), with a single broader maximum approximately encompassing the phase interval covered by both X-ray peaks, and centred on the first harmonic X-ray peak (Figure 2). This suggests that the optical and X-ray emitting regions are somehow linked and that the former is likely more extended.

The HR shows hardening at orbital minimum and the intensity of the orbital modulation decreases with energy. These findings im-
Table 7. Spectral parameters at maximum (Max) and minimum (Min) of the orbital modulation (Orb.). Other parameters are fixed to their average spectrum best-fit values. Uncertainties are at 1σ confidence level.

| source Orb. | N_{He+1} | cvf | N_{He+2} | cvf | F_{0.3–10} | χ^2/dof |
|-------------|----------|-----|----------|-----|------------|---------|
| J0927 Max   | 3.8(3)   | 79(1) | 29(1)    | 74(2) | 5.4(1)    | 1.34/296 |
| J0927 Min   | 6.9(7)   | 93(1) | 38(2)    | 78(3) | 4.2(1)    | 1.14/172 |
| J2113 Max   | 3.3(5)   | 64(4) | 12(2)    | 37(7) | 9.9(1)    | 0.97/344 |
| J2113 Min   | 4.4(4)   | 89(1) | 30(4)    | 47(4) | 7.7(2)    | 0.86/225 |

We fitted the average broad-band spectrum (Table 4 and Figure 3) with a single MEKAL (kT = 12.6±0.3 keV) plus a Gaussian (EW = 140 ± 20 eV), multiplied by PHABS (N_{He+1} = 6 ± 1 x 10^{20} cm^{-2}) and two PCfabs (N_{He+1} = 4.7 ± 0.4 x 10^{22} and N_{He+2} = 3.3 ± 0.4 x 10^{22} cm^{-2}). We got a slightly high χ^2 (1.3 for 294 d.o.f.), also because of the residuals below 1.5 keV. Unfortunately, data from the RGS cannot help in resolving residual features, since the source is heavily absorbed. The relatively low temperature of the emitting plasma, although being an average over the post-shock region, may indicate that the WD is not massive. Indeed, the PSR model gives a WD mass of 0.58 ±0.06 M_☉ (Table 5).

The spectrum at pulse minimum is more absorbed. The Pc1 parameters increase by a factor of ∼2.2 (N_{He+1}) and of ∼1.2 (cvf_{Pc1}). We conclude this is the main cause of the X-ray pulse. The high column density absorber (Pc2) is in fact constant within uncertainty (Table 6). The spectrum at orbital minimum is also affected by absorption. However, if both Pc1 and Pc2 parameters are left free to vary, Pc1 is still the dominant component (Table 7). Due to the low S/N we are not able to infer spectral changes along the spin period at orbital maximum and minimum.

Energy dependent X-ray orbital modulations have been observed in a number of IPs (Parker, Norton & Mukai 2005; Bernardini et al. 2012) indicating that material fixed in the binary frame, such as the stream impact point at the outer disc rim, could produce additional absorption. Since J0927 show evidence of a partial disc-overflow accretion mode, this interpretation seems well justified.

4.4.3 An IP above the gap

J0927 shows temporal and spectral characteristics of a typical IP. A tentative distance of 240 pc was derived adopting an absolute magnitude of M_v = 0.0 (Parisi et al. 2014). We here try to constrain the source distance as follows. The low column density of the total absorber suggests low extinction. Using the relation by Güver & Özel (2009) an upper limit to the interstellar extinction is derived: A_V < 0.2. J0927 is also identified as 2MASS J09275308-6944 with J = 14.823 ± 0.042, H = 14.642 ± 0.062 and K = 14.311 ± 0.084 mag, and as WISE J092752.94-694442.3, with W1 = 14.273 ± 0.059, W2 = 14.005 ± 0.052 and W3 = 13.459 ± 0.42 mag. The reddened nIR colours J-H = 0.15 ± 0.07 and H-K = 0.32 ± 0.1, indicate the presence of more than one spectral component. The J-H colour would suggest a mid F-type star, but the H-K index would give a spectral type M2–M6 (Straižys & Lazauskaitė 2009). The mid-IR colour W1-W2 = 0.27 ± 0.08 also indicates a spectral type later than M4 (Pecaut & Mamajek 2013). A M2.3 V donor is expected in a 5.15 h binary (Smith & Dhillon 1998; Knigge 2006). Since later spectral type than M4 would imply a system below the gap, we assume a donor in the range M2–M4 (hence absolute magnitudes M_K = 5.16 – 7.69, Knigge 2006) and use the dereddened K-band magnitude to estimate the distance that results in the range ∼ 210 – 670 pc. While this encompasses the value found by (Parisi et al. 2014), it poses a more stringent upper limit to the distance.

We then evaluate the accretion luminosity and then accretion rate in J0927. Also in this case the contribution of reprocessed radiation cannot be determined with the present data. Using the upper limit of 670 pc, L_{acc} ∼ L_{bol, bol} ≲ 1.2 x 10^{33} erg s^{-1}, which in turn translates into a mass accretion rateṀ = 2.2 x 10^{-10} M_☉ yr^{-1} for a 0.58 M_☉ WD mass (Table 5). This is ∼ 2 orders of magnitude lower than the secular mass transfer rate expected for a binary evolving through magnetic braking in a 5 h orbit (McDermott & Taam 1989; Howell, Nelson & Rappaport 2001). Lower mass transfer rates than predicted by the present-day CV population models were also recently found in a number of CVs above the gap (see Pala et al. 2017). While diversities in their secular properties are expected for selected CV populations (Goliasch & Nelson 2015), any conclusion needs to await accurate GAIA parallaxes.

The spin-orbit period ratio is P_c/P_Ω ∼ 0.06, as it is for most of the IPs observed above the orbital period gap and accreting via a disc truncated at the magnetospheric radius (see Norton et al. 2008). For a WD spinning at equilibrium, the corotation radius (R_{cr} = (G M_{WD} P_{Ω}^3/4 π^2)^{1/3}) is defined as the radius at which the magnetosphere rotates at the expected Keplerian frequency for that radius, balances the Alfvén radius, R_A = 5.5 x 10^{8} (M_{WD}/M_☉)^{1/7} R_{cr}^{2/7} L_{bol}^{-2/7} L_{bol}^{4/7} cm. Here μ is the magnetic moment in units of 10^{20} G cm^{-3}, L_{bol} is the luminosity in units of 10^{33} erg s^{-1}, and the WD mass and radius are in solar and 10^{9} cm units, respectively. Adopting P_c=1303.54 s, the luminosity determined above, M_{WD} = 0.58 M_☉ and R_{WD} = 8.8 x 10^{8} cm, a magnetic moment μ ∼ 5 × 10^{33} G cm^{-3} is inferred. This is the end of low magnetic moments expected for slow rotators Norton et al. 1999: Norton, Wynn & Somerscales 2004, as it is the WD in J0927, but it depends on the assumed accretion luminosity.

J0927 appears a typical IP above the period gap and caught in an hybrid accreting mode, which is not uncommon in long period systems (see Norton et al. 1997; Beardmore et al. 1998; Knigge 2006).

4.5 Swift J0958.0-4208

J0958 was identified by Masetti et al. 2013 as a CV, possibly of the magnetic type through optical spectroscopy.

4.5.1 Timing analysis

The X-ray power spectrum shows a strong peak corresponding to a period of 296.22 ± 0.05 s that we interpret as the WD spin period and a much weaker feature at its first harmonic (Table 2). There is no sign of these short-term periodicities in the optical (B-band).
power spectrum. The inspection of the X-ray light curve suggests that long-term X-ray variability (on a timescale of $\sim 8$ h) could be present, although consistent with the length of the pointing. A possible variability on a timescale of $\sim 2.2$ h may be present in the optical band, but does not appear to be periodic. J0958 is also a variable source (CSS.J095750.7-420836) monitored in the Catalina (CRTS) survey from 2006 to 2013, but a search for periodicities less than a day did not give conclusive results. Thus, the orbital period of this system remains unknown.

The PF decreases as the energy increases (Table 3 and Figure 2) from a maximum of about 38 per cent in the 0.3–1 keV band to a minimum of about 7 per cent in the 5–12 keV band. The HR shows hardening at spin minimum, as found in the majority of IP systems. J0958 seems to be an IP dominated by its spin period and therefore a pure disc accretor.

4.5.2 Spectral analysis

The best fit model (Table 3 and Figure 1) consists of a MEKAL (kT = 36 ± 13 keV) plus a blackbody (kT = 79 ± 3 eV) and a Gaussian (E= 190 ± 20 eV), absorbed by a total PHABS (N_{H} = 2.6 ± 0.4 × 10^{21} cm$^{-2}$) and a partial covering absorber PCfabs (N_{H,p} = 16.5 ± 1.9 × 10^{23} cm$^{-2}$). Metal abundances are consistent with solar value. No additional optically thin component is required. The blackbody component is hot, but not unusual as found also in other soft IPs (see Haberl, Motch & Zickgraf 2002; Anzolin et al. 2008; Bernardini et al. 2012). The column density of the total absorber is within 2σ consistent with that in the direction of the source (N_{H,gal} = 1.6 × 10^{22} cm$^{-2}$). The fit with the PSR model gives M_{WD} = 0.74 ± 0.12 M$_{\odot}$ (Table 3), which is consistent within uncertainties with that resulting when adopting a 56 keV maximum temperature ($\sim$0.8M$_{\odot}$). The main changes in the spectral parameters with the spin period are related to variations in the normalization of the MEKAL, which increases in spin maximum by a factor of $\sim$1.4. The cdf of PCfabs also slightly increases at pulse minimum (69 ± 2 vs 61 ± 3 per cent), but not its column density. The other parameters remain constant within uncertainties (Table 3). The lack of variability of the blackbody normalization indicates that the irradiated polar cap of the WD remains visible along the whole spin pulse.

The bolometric soft-to-hard flux ratio defined as Fsoft/Fhard (see Ramsay & Cropper 2004b) is 0.09, similar to those found in other soft IPs with comparable hot blackbody temperature (Anzolin et al. 2008; Bernardini et al. 2012). The reprocessed X-ray emission would then originate from a small polar region as inferred from the normalization of the blackbody: $A_{X} \sim 0.65 - 3.4 \times 10^{13}$ cm$^{-2}$ for a distance in the range 0.72–1.1 kpc (see below). Indeed, adopting a M_{WD} = 0.74 M$_{\odot}$ and its corresponding $5.7 \times 10^{8}$ cm radius, a fractional area $f \sim 0.1 - 6 \times 10^{-6}$ is obtained.

4.5.3 A fast spinning IP

J0958 shows typical IP characteristics. A tentative distance of 200 pc was derived by Masetti et al. (2013) using similar arguments as in J0927 by (Parisi et al. 2014). We here estimate the distance using

10 http://crts.caltech.edu/
11 The PF is calculated removing the last 12 ks of EPIC exposure which are affected by high background activity
also detected in the simultaneous OM B-band photometry, where the flux drops by a factor of $\sim 3$. An archival $XMM$-$Newton$ observation (obsid: 0743200101) of the planetary nebula PN G343.3-00.6=PN HaTr5, which is only 17 arcsec apart from J1701 was carried out on 2014-08-31 for 14 ks. J1701 is serendipitously detected in the EPIC exposures as a bright source overwhelming PN G343.3-00.6, which is instead not detected. At the beginning of this pointing, the final part of a total X-ray eclipse clearly appears. This shows that this feature is real and that J1701 is a deep eclipsing CV. The lack of consecutive eclipses in both $XMM$-$Newton$ observations implies an orbital period $\gtrsim 4.4$ h.

The ground-based optical and nIR photometry (Section 2.4) also displays eclipses in all bands. The $LCO$ photometry caught one full eclipse and another only partially. Four eclipses are instead detected in the REM data, and seven in the $AAVSO$ photometry. To determine the orbital period the combined $g'$ and $V$-band light curves were analysed with the $PERIOD04$ package. The power spectrum reveals a strong peak at 1.87 d$^{-1}$ and period analysis gives $P_{\text{g'}} = 0.53413 \pm 0.00002$ d, and epoch of minimum $T_0$(BJD) = 2457660.53569$ \pm 0.00003$. An improved ephemeris was obtained extending the baseline with the $LCO$ $g'$-band (June 2016) and the OM $B$-band data (2015). Each of the 13 eclipses was fitted with a Gaussian to obtain the times of minima. A linear regression was used to obtain the following ephemeris:

$T_0(\text{BJD}) = 2457599.66277 \pm 0.00009$ and $P_0 = 0.534026 \pm 0.000005$ d. Observed-minus-calculated ($O-C$) residuals were inspected against trends, showing that a constant period gives an acceptable fit. The excursions on average are within 240 s around zero. The eclipse depths derived from Gaussian fits are: $\Delta g' = 0.96 \pm 0.03$, $\Delta r' = 0.72 \pm 0.04$, $\Delta i' = 0.59 \pm 0.03$, $\Delta B = 1.27 \pm 0.07$, $\Delta V = 0.68 \pm 0.02$ and $\Delta J = 0.30 \pm 0.08$ mag. The width of the optical eclipses (FWHM) are instead consistent within errors (2765 $\pm 90$ s). The X-ray eclipse lasts 2920 $\pm 30$ s and is total for 2747 $\pm 15$ s. The egress appears slightly asymmetric since it happens at the peak of a spin pulsation (Figure 5). To measure the $e$-folding times we fitted the light curve (14 s binned) outside the eclipse with two sinusoids to account for the X-ray spin pulse, and with an exponential decay/rise to model the ingress/egress time and found $\tau_{\text{ingress}} = 94 \pm 42$ s and $\tau_{\text{egress}} = 63 \pm 14$ s (Figure 5).

### The spin pulsation

The X-ray persistent emission further displays a periodic modulation. The PN power spectrum has a strong peak at $\sim 5.5 \times 10^{-4}$ Hz and its first harmonic. No other signal is detected. By removing the eclipse interval, a composite two-sinusoidal fit gives: $P_X = 1859 \pm 3$ s (Table 2).

The OM $B$-band light curve also displays similar periodic variability. A sinusoidal fit does not require the first harmonic and gives $P_X^{\text{om}} = 1857 \pm 6$ s, fully consistent with the X-ray period. We used the $AAVSO$ $V$-band light curve to improve the measure of the spin period. A fit with two-sines to model the fundamental and its first harmonic gives $P_X^{\text{om}} = 1858.67 \pm 0.02$ s. This period is adopted to fold and study the X-ray pulse properties (Table 2). Both the X-ray and optical ($B$ and $V$ bands) pulses are in phase indicating a common origin. The X-ray PF decreases from 70 per cent in the 0.3–1 keV band to 18 per cent in 5–12 keV band (Figure 2) and Table 3, suggesting that photoelectric absorption is the main cause of the X-ray spin pulsation.

#### 4.6.2 Spectral analysis

The best fit to the average broad-band spectrum (Table 3 and Figure 3) consists of two $\text{MEKAL}$ ($kT_0 = 6.0^{+0.5}_{-0.3}$ keV and $kT_0 \geq 54$ keV, $3\sigma$ lower limit), plus a blackbody ($kT_{BB} = 53 \pm 1$ eV) and a 6.4 keV Gaussian (EW=110 $\pm$ 30 eV). The hydrogen column density of the total absorber is $N_H = 7.6 \pm 0.4 \times 10^{21}$ cm$^{-2}$ and that of the partial is $N_{HI} = 7.7^{+0.7}_{-0.4} \times 10^{22}$ cm$^{-2}$ with $c_{\text{evl}} = 65 \pm 1$ per cent ($\chi^2 = 1.1$ for 366 d.o.f). The metal abundance is high ($A_Z = 2.3 \pm 0.4$), though consistent with solar values within $\sim 3\sigma$. The BAT inter-calibration constant is 0.50 $\pm$ 0.07, suggesting that the sources could be variable on the long-term and that when observed by $XMM$-$Newton$, it was brighter than the average over many years. Despite its hard spectrum, a reflection component is not required. Furthermore, the PSR model gives a massive WD ($1.16^{+0.13}_{-0.11} M_\odot$). This high value is consistent with the lower limit obtained for the hot $\text{MEKAL}$ component ($M_{WD} \geq 0.97 M_\odot$).

The HR shows an hardening at spin minimum. The equivalent hydrogen column and the covering fraction of the partial covering absorber both increase at spin minimum by a factor of $\sim 1.4$ and $\sim 1.6$, respectively. The normalization of the hot $\text{MEKAL}$ slightly increases by a factor of about 1.4 at maximum. On the other hand, the blackbody normalization increases by a factor $\sim 1.7$ at spin minimum, indicating this component arises from the heated WD.
atmosphere at the poles. Similarly, the EW of the 6.4 keV fluorescent line also increases from 110 eV at spin maximum to 180 eV at spin minimum, suggesting that reflection occurs at the WD poles (Table 6).

We derive a bolometric flux ratio \( F_{\text{soft}}/4F_{\text{hard}} \sim 1.95 \), which is the highest ever inferred in a soft X-ray IP and closer to that observed in polars.\(^{\text{13}}\) Although subject to model uncertainties, the emitting area of the WD hot spot is \( 4.1 \times 10^{15} \text{cm}^2 \) at a distance of 1 kpc (see below). This would correspond to a large fractional area, \( f \sim 1.5 - 3.9 \times 10^{-3} \), of a WD with \( M_{\text{WD}} \sim 1.1 M_\odot \).

### 4.6.3 A deep eclipsing long period IP

The multi-band photometry has been analysed to unveil the donor star and system parameters. Using the B, V, g, r, i, and J bands magnitudes (Figure 5), the spectral energy distributions outside and at eclipse minima were constructed. We applied a reddening \( A_V = 3.17 \) derived assuming that the PHABS absorber, which \( 1\sigma \) lower error is \( N_H = 7.2 \times 10^{21} \text{cm}^{-2} \), is entirely interstellar and then applying the extinction relation by Güver & Özel (2009). Although this source lies in a heavily reddened region of the Galactic Plane, a higher extinction is disfavoured by inspection of the optical spectrum by Masetti et al. (2013), where weak DIBs are identified. Fitting the SED at eclipse minimum with a blackbody gives a temperature of \( 7.3 \pm 0.3 \text{kK} \) indicating a relatively hot donor. The optical spectrum presented in Masetti et al. (2013) also reveals the Mg b feature at 5167-5184 Å, which was compared with stellar templates from the Pickles catalogue.\(^{\text{14}}\) With spectral types in the range F0–G0 V using several reddening values. The best match is found for a F0–F5 V spectral type with \( A_V = 3.1 \), in agreement with the SED at eclipse minimum, with the mid-F spectral type being preferred. The contribution of the donor star to the total V-band flux outside the eclipse is \( \sim 53 \) per cent.

While a detailed analysis and fine tuning of the optical/nIR light curves will be presented in a forthcoming work, first estimates of the binary system parameters, the mass ratio \( q \), the inclination \( i \), and the donor star temperature were obtained with the NOiGHTFALL code (v.1.88)\(^{\text{15}}\) applied simultaneously to the most covered orbital light curves in V, g, r, i, and J bands. These were fitted adopting a Roche-lobe filling donor star and a primary treated as a point source with fixed temperature of 200 kK (e.g. the higher allowed temperature). An irradiated accretion disc with fixed inner and outer radii of 0.01 and 0.40 in units of the WD Roche-lobe was also included. The disc thickness was set to 1 per cent and the temperature of the inner disc boundary and of the hot-spot at the outer disc rim to 30 kK and 8 kK, respectively.\(^{\text{16}}\)

The donor temperature, \( q \), and \( i \) were left free to vary obtaining \( q = 0.87 \pm 0.02 \), \( i = 72 \pm 2 \) deg and \( T_2 = 7.2 \pm 0.4 \) kK (\( \chi_i^2 = 5840 \) for 5640 dof). The large \( \chi_i^2 \) is due to the large scatter and small errorsbars (typically 3 per cent) of the photometric measures and to the approximate modeling of the eclipse feature. Due to the extent of the wings of the eclipse a larger accretion disc is disfavoured (see also Horne, Gomez & Laming (1982)). Adopting \( M_{\text{WD}} = 1.16 \pm 0.13 M_\odot \), the donor would have \( 0.7 \lesssim M_2 \lesssim 1.4 M_\odot \).

The length of the X-ray eclipse, and particularly the time elapsed from the first to the 3rd contact, (or the 2nd and 4th contact) \( \Delta \phi_{\text{acc}} \approx 0.06 \), allows the placing of constraints on the donor star radius in units of binary separation: \( R_2/a \approx (\sin^2 (\pi \Delta \phi) + \cos^2 (\pi \Delta \phi) \times \cos^2 i)^{1/2} / (2 \times \Omega) \). Asking a Roche-lobe filling secondary, this equation, together with the equivalent Roche lobe radius approximation by Eggleton (1983), define an unique relation between \( q \) and \( i \). Adapting the \( 1\sigma \) uncertainty on \( q \), \( i \) and \( M_{\text{WD}} \) as a range, this restricts the orbital separation to \( a \sim 3.33 - 3.87 R_\odot \) and the donor radius to \( R_2 \sim 1.14 - 1.48 R_\odot \). The secondary appears to be expanded and evolved, in line with the expected present-day population of CVs with evolved donors at these long orbital periods (Goliasch & Nelson (2013)).

Adopting the range of the donor radius and using the normalization obtained from the fits to the SED during the eclipse, a distance of 995–1290 pc is obtained. We then adopt a distance of 1 kpc for J1701.

Furthermore, an estimate of the X-ray emitting region \( R_\text{x} = (v_1 + v_2) / 2 \Delta T_{\text{egress}} \) is also derived. Here \( \Delta T_{\text{egress}} = 63 \pm 14 \) s and \( v_1 \) and \( v_2 \) are the primary and secondary relative velocities. From Kepler’s third law: \( v_1 + v_2 = (2 \pi G (M_1 + M_2) / P_1)^{1/3} \sin i \). Adopting the \( 1\sigma \) uncertainties on the WD and donor masses, inclination and egress time, we obtain \( R_\text{x} \sim 0.7 - 1.3 \times 10^3 \) cm, which is \( 1.3 - 3.4 \) times the radius of the massive WD. Taken at its face value, this would suggest a very extended X-ray emitting region. Post-shock regions are only a few percent the WD radius (see Mukai (1999)). To account for such large linear extension, two opposite emitting poles should be visible at the same time, as suggested by the presence of the harmonic of the spin frequency, and in turn they should be gradually hidden during the eclipse ingress/egress.

Adopting for the accretion luminosity \( L_{\text{acc}} \sim L_{\text{x,thin}} + L_{\text{x,soft}} \), at a distance of 1 kpc it results in \( 4.9 \times 10^{34} \text{erg s}^{-1} \). For a \( M_{\text{WD}} = 1.16 M_\odot \), we derive \( M \sim 2 \times 10^{-9} M_\odot \text{yr}^{-1} \) (Table 5). At long (\( \sim 8 - 10 \) h) orbital periods, donors in CVs are expected to have high mass transfer rates and to be chemically evolved (Goliasch & Nelson (2015)). The inclusion of nuclear evolution in the synthesis models of the present-day CV population allows the attainment of longer (\( \gtrsim 10 \) h) periods and a wide range of mass-transfer rates, including the value inferred here for J1701. The probability of finding such very long period systems is however low, about 1 per cent.

J1701 is one of the longest orbital period IP. It is surpassed only by GK Per (47.9 h) and V2731 Oph (15.4 h). These are highly asynchronous systems \( (P_2 / P_1 \sim 0.002) \), while J1701 has \( P_2 / P_1 = 0.04 \). Accounting for the high mass ratio inferred, the observed asynchronous in J1701 is consistent with a WD spinning at equilibrium (Wynn & King (1995), King & Wynn (1999)) and accreting via a disc (Norton et al. (2008)). We then derive a magnetic moment \( \mu \sim 5 \times 10^{38} \text{G cm}^{-3} \). Though to be regarded with caution, this large value would suggest that J1701 will evolve into a Polar when reaching synchronism (Norton, Wynn & Somerscales (2004)).

J1701 is then the first deeply eclipsing IP ever found at long orbital periods and adds to the small group of eclipsing systems of this class: EX Hya, XY Ari, IPHAS J062746+0148, V597 Pup, and DQ Her (Heller (2014), and references therein), and the two recently discovered IPs SWIFT J201424.9+152930 (Esposito et al. (2015)) and CXOGJS J174954.5-294335 (Johnson et al. (2017)). In addition, IGR J18293-1213\(^{\text{17}}\) is definitely an eclipsing CV and may well be an eclipsing IP. Time-resolved optical/nIR polarimetry will be crucial to understand the evolution of this IP and the interaction of the accretion flow with the magnetosphere.

\(^{13}\) http://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html

\(^{14}\) Details of parameters setting can be found in the NOiGHTFALL User Manual

\(^{15}\) http://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html

\(^{16}\) http://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html

\(^{17}\) http://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html
4.7 Swift J2113.5+5422

J2113 was tentatively proposed by Masetti et al. (2010), as a magnetic CV of the IP type given the strength of its He II emission line. It appears as 1RXS J211336.1+542226 in their work.

4.7.1 Timing Analysis

The X-ray power spectrum clearly shows three peaks, pointing to three periodic signals. A broad peak at low frequency $6.9 \times 10^{-5} \text{ Hz}$, together with two close peaks at $7.3 \times 10^{-4} \text{ Hz}$ and $7.9 \times 10^{-4} \text{ Hz}$. We then identify the highest frequency peak as the WD spin and the close one as the beat ($\omega - \Omega$), while the broader low-frequency peak as the binary frequency ($\Omega$). Indeed, the X-ray light curve fully samples three orbital cycles (Figure 1) with $P_{\Omega,SC} = 4.02 \pm 0.10 \text{ h}$. We further measure $P_{\omega - \Omega} = 137.35 \pm 2.68 \text{ s}$ and $P_{\omega} = 1265.61 \pm 4.51 \text{ s}$ (Table 3). Using the beat and spin frequency a period $P_{\Omega,Side} = 4.46 \pm 0.10 \text{ h}$ is obtained. It is longer than $P_{\Omega,SC}$, but consistent within $3\sigma$. The OM V-band light curve instead does not show any short-term periodicity, but rather large flickering (Figure 1). It is modulated at a period $P_{\Omega,pt} = 3.63 \pm 0.11 \text{ h}$, which is shorter, but consistent within $3\sigma$, with the X-ray value. The amplitude of the optical modulation is smaller than that in the X-ray band ($16 \pm 2 \text{ vs } 29 \pm 1 \text{ per cent}$; Figure 1). The intensity of the spin modulation in the whole 0.3–12 keV range is low (PF~15 per cent), but we still measure a higher PF at lower energies (ranging from 30 per cent in the softest range to 9 per cent in the hard band. (Table 3 and Figure 2). The HR varies along the orbital period, with the system being harder at the orbital minimum. The intensity of the orbital modulation also decreases with energy. All these findings suggest that photoelectric absorption is the main cause of both the spin and orbital modulations. As in the case of J0927, the fact that the orbital X-ray modulation is energy dependent suggests that the X-ray emission is absorbed by material fixed in the binary frame, such as the outer disc rim. The amplitude ratio of the two short-period X-ray modulations is $A_X^N/A_X^{Side} \approx 1.1$, indicating that the system is in a disc-overflow accretion mode.

4.7.2 Spectral analysis

We fitted the average broad-band spectrum (Table 3 and Figure 3 with two MEKAL (kT$_{e} = 4.0 \pm 0.5\text{ keV}$ and kT$_{b} = 31 \pm 7\text{ keV}$) plus a Gaussian, absorbed by a total PHABS ($N_{H,ph} = 7.4 \pm 0.4 \times 10^{21}\text{ cm}^{-2}$) and two partial covering columns PCFABS ($N_{H,pc1} = 3.7 \pm 0.5 \times 10^{22}\text{ cm}^{-2}$ and $N_{H,pc2} = 1.7 \pm 0.5 \times 10^{23}\text{ cm}^{-2}$) ($\chi^2 = 1.05$ for 370 d.o.f.). We note that the BAT inter-calibration constant is $0.60 \pm 0.12$, which may suggest that the source is variable on the long-term and that we observed it in a state brighter than the average over many years. The EW of the 6.4 keV fluorescent line is very small (70 eV), indicating that reflection is not important in the hard X-ray portion of the spectrum. The column density of the total absorber ($N_{H,pt}$) is consistent with the galactic hydrogen column density in the source direction ($N_{H,gal} = 8.5 \times 10^{21}\text{ cm}^{-2}$). Kaperla et al. (2005). The PSR model gives a WD mass of $0.81 \pm 0.01\text{ M}_\odot$, consistent within uncertainties with that resulting from the hot MEKAL component (Table 4).

Also because of the weak spin modulation, the pulse resolved spectroscopy only shows marginally significant changes. The spectrum is slightly harder at pulse minimum, where cfv$_{1}$, the covering fraction of the lower density absorber (Pc1), increases by a factor of $\sim 1.2$ (Table 5). On the other hand, the spectrum at orbital minimum is clearly harder, mainly due to the increase by a factor $\sim 2.5$ of the hydrogen column density of the second partial covering absorber (Pc2) and a to a slight increase of cfv$_{2}$, its covering fraction (see Table 7). Therefore, this higher density absorber is mainly responsible for the orbital modulation. The spectral analysis then clearly shows that two different absorbers are responsible for the spin (Pc1) and the orbital (Pc2) modulation. They can be ascribed to the magnetically confined pre-shock flow and matter accumulating at the disc rim, respectively.

4.7.3 An IP above the period gap

J2113 lies close to the galactic plane ($b \sim 4^\circ$) and thus interstellar extinction in the direction of the source is high. We then adopt the column density of the total absorber ($N_{H,pt} = 7.4 \times 10^{21}\text{ cm}^{-2}$) as an upper limit to the interstellar extinction in the source direction, which translates into $A_V = 3.3$ (Güver & Ozel 2009). Also for J2113 we estimate the distance using nIR and mid-IR data. However, J2113 is not a 2MASS source, but surprisingly it appears as WISE J211335.41+542233.0 with $W1 = 14.985 \pm 0.038\text{ and } W2 = 14.519 \pm 0.048\text{ mag}$. The reddened colour $W1-W2 = 0.43 \pm 0.06$ would indicate a very low temperature component $\sim 1800\text{ K}$. For a 4.1 h orbital period binary, the donor should have a spectral type of M3.4 V star (Knigge 2004), and thus much bluer colours ($W1-W2 < 0.12$). This points to an excess of flux, as also found in some CVs. It could be due to circumbinary dust emission or, as seen in J0706, low-harmonic cyclotron flux in the case of polars. Further analysis is beyond the scope of this paper, but investigation in the IR is needed to unveil the true nature of the excess in this system. From the lack of detection in the 2MASS survey, we estimate an upper limit to the K-band flux (lower limit magnitude of $K > 15.4$) in a region close to the position of the source in the 2MASS survey. This, corrected for interstellar extinction, translates into a lower limit to the distance of 750 pc, adopting a M3.6 V star with $M_K = 6.3$ (Knigge 2004). A rough $\sim 1.6\text{ kpc}$ distance would instead result using the extinction-distance relation as a function of galactic latitude.

The accretion luminosity is then evaluated as: $L_{acc} \sim L_{X,bol} \gtrsim 1.7 \times 10^{33}\text{ erg s}^{-1}$ adopting conservatively $d = 750\text{ pc}$. For a WD mass of $0.81\text{ M}_\odot$ (Table 5), this translates into $M_X \gtrsim 1.7 \times 10^{-10}\text{ M}_\odot\text{ yr}^{-1}$. As a lower limit it could be consistent with those of long period systems (Howell, Nelson & Rappaport 2001).

J2113 is then an IP above the gap with a typical spin-to-orbit period ratio of $\sim 0.00$. For a WD spinning at equilibrium a magnetic moment $\mu \gtrsim 6 \times 10^{22}\text{ G cm}^{-3}$ is derived, consistent with a moderately magnetic slow WD rotator. This system is then another example of a disc-overflow accretor above the orbital gap.

5 CONCLUSIONS

The broad-band analysis presented here unambiguously reveals the magnetic nature of five hard X-ray selected CV candidates. We indeed classify J0927, J0958, J1701, and J2113 as firm IPs. We suggest that J0801 is also an IP, although possibly displaying an atypical spectrum. J0706 is instead a polar, joining as the 11th member the group of hard X-ray selected polars. One system, J0746, is found to accrete at an extremely low rate for its long orbital period (9.38 h). The lack of periodic variations in its X-ray light curve does not support the magnetic CV membership. It could be either an atypical low-luminosity CV or even a LMXB, although evidences for this interpretation are not compelling.

The class of IPs has grown substantially over the last decade.
(see e.g. Ferrario, de Martino & Gänsicke 2015), now amounting to 66 systems (with 10 of them identified in the last two years, Bernardini et al. 2015; Esposito et al. 2015; Coti Zelati et al. 2016; Tomick et al. 2016; Johnson et al. 2017). This is about half of the size of the Polar class (~110 members).

While IPs were already known to populate the orbital period distribution above the 2–3 h gap, the new identifications have revealed systems with longer periods (e.g. above 6 h). At present there are 14 such IPs that represent ~10% of the whole CV population in this period range. These long period systems have probably entered in the CV phase with evolved donors and their spin-orbit period ratios (Figure 5 left panel) suggest they will reach synchronism while evolving to short orbital periods. Furthermore, 10 IPs are found below the orbital period gap, where they are not expected (Norton, Wynn & Sommerscales 2004; Norton et al. 2008), indicating that they will likely never synchronise. They have low X-ray luminosity, with four identified in the hard X-ray surveys (EX Hya, V1025 Cen, DO Dra, and IGR J18173-2509) at only \( L_{\text{X}} \sim 10^{31} \text{erg s}^{-1} \). J0801 has a similar luminosity and may in future join this group, once its orbital period is measured. Finding new low-luminosity IPs is crucial to confirm the suggestion that short-period IPs are intrinsically common as the more luminous long-period IPs (Pretorius & Mukal 2014). Furthermore, seven out of the 11 polys detected in the hard X-ray surveys, including the last addition of J0706, are also found at similar luminosities. Whether magnetic systems, and particularly IPs, are major constituents of the Galactic Centre X-ray emission (GCXE) and of GRXE is still largely debated. A recent re-evaluation using both XMM-Newton and NuSTAR observations of the inner central (few pc) regions of the Galaxy (Hailey et al. 2016) shows that relatively massive (~0.9 \( M_\odot \)) magnetic WDs can account for the X-ray luminosity function at \( \sim 5 \times 10^{31} \text{erg s}^{-1} \). WDs in IPs are indeed found to be relatively massive (Brunscheier et al. 2006; Yuasa et al. 2010; Bernardini et al. 2012, 2013b; Tomick et al. 2016) as is the case for the majority of the sources in our sample (where \( M_\text{WD} < \sim 0.88 M_\odot \)). This is broadly in line with the general finding that WD primaries in CVs are more massive than single WDs and WDs in pre-CV binaries, in contrast with predictions of standard CV formation theory. This disagreement led to suggest that either the WDs grow in mass during CV evolution, or a significant fraction of the observed population of CVs has formed through a preceding short phase of thermal timescale mass transfer (TTMT), during which the WD substantially increases in mass (Zorotovic, Schreiber & Gänsicke 2011). However, neither the inclusion of a TTMT phase nor the adjustment of the accretion efficiency to allow the WD mass growth in binary population synthesis models (Wienen, Zorotovic & Schreiber 2015) are able to explain the observed WD mass distribution in CVs, leaving the issue still unsolved. Furthermore, other recent studies may indicate that the GRXE is not composed primarily of IPs, but rather by non-magnetic CVs and polars (Reis et al. 2013; Warwick, Bryckling & Pérez-Ramírez 2014; Xu, Wang & Li 2016), with IPs populating the harder tail. Thus, this issue may eventually be solved with the identification of a larger sample of low-luminosity MCVs and IPs in particular.

Our study has also revealed additional systems displaying a soft X-ray blackbody component with temperatures ranging from those observed in the polars (\( \sim 40 - 60 \text{ eV} \)) as in J1701, to higher values (\( \sim 80 \text{ eV} \)) as in J0958, with distinct softness ratios. Since the time of the compilation by Anzolin et al. 2008 the current roster of “soft” IPs increased and now amounts to 19 systems (Figure 6, right panel), representing ~30% of the whole subclass.

Although high blackbody temperatures arising from the WD surface would be locally super-Eddington, the possibility that the soft component originates instead in the coolest regions of the accretion flow (e.g. above the WD surface) is not supported by the spectral fits. On the other hand, J0706 adds to the increasing number of polys discovered without a detectable soft component (see e.g. Ramsay et al. 2009; Bernardini et al. 2014; Worpel et al. 2016). This soft component was initially considered the defining characteristics of highly magnetic systems, but XMM-Newton has demonstrated that not to be the case. Whether this component is in some cases cool and thus simply shifted to the EUV band, will be difficult to assess due to the lack of foreseen facilities in this energy range.

We also note that the spectra analysed here can simply be modeled with a one or two temperature emitting plasma (although a more physical model is also used), likely because we are sampling X-ray faint targets, where the fine details of the spectra are hidden in the noise. A detailed mapping of the plasma conditions in the post shock region with high resolution X-ray spectroscopy is clearly needed. It will also help in solving the puzzle of the hot and locally super-Eddington blackbody component. However, all this will need to await the next generation of X-ray telescopes, like Athena.

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Figure 6. Left: The spin-orbit period plane of confirmed IPs (crosses) with those identified in the hard Swift and INTEGRAL surveys denoted with filled circles. Upper and right panels report the orbital (except for J0801 and J0958) and spin period distributions of the confirmed systems including the sample presented in this work. Confirmed IPs are taken from Ferrario, de Martino & Gänsicke (2015); Bernardini et al. (2015); Esposito et al. (2015); Coti Zelati et al. (2016); Tomick et al. (2016); Johnson et al. (2017). Right: The softness ratio of polars (filled triangles) and of soft IPs (open circles) versus blackbody temperature. Values for polars are taken from Ramsay & Cropper (2004b) and for IPs from Anzolin et al. (2008); Masetti, Nucita & Parisi (2012); Bernardini et al. (2012); Joshi et al. (2016) and this work.

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