Very fast photometric and X-ray observations of the intermediate polar V2069 Cygni (RX J2123.7+4217)

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ABSTRACT
We present fast timing photometric observations of the intermediate polar V2069 Cygni (RX J2123.7+4217) using the Optical Timing Analyzer (OPTIMA) at the 1.3-m telescope of Skinakas Observatory. The optical (450–950 nm) light curve of V2069 Cygni was measured with sub-second resolution for the first time during 2009 July and revealed a double-peaked pulsation with a period of 743.38 ± 0.25 s. A similar double-peaked modulation was found in the simultaneous Swift satellite observations. We suggest that this period represents the spin of the white dwarf accretor. Moreover, we present results from a detailed analysis of the XMM–Newton observation, which also shows a double-peaked modulation, however shifted in phase, with a period of 742.35 ± 0.23 s. The X-ray spectra obtained from the XMM–Newton European Photon Imaging Camera (EPIC) instruments were modelled by a plasma emission and a soft blackbody component with a partial covering photoelectric absorption model with a covering fraction of 0.65. An additional Gaussian emission line at 6.385 keV with an equivalent width of 243 eV is required to account for fluorescent emission from neutral iron. The iron fluorescence (~6.4 keV) and Fe xxvi lines (~6.95 keV) are clearly resolved in the EPIC spectra. In the $P_{\text{orb}}$–$P_{\text{spin}}$ diagram of intermediate polars, V2069 Cyg shows a low spin-to-orbit ratio of ~0.0276 in comparison with ~0.1 for other intermediate polars.

Key words: binaries: close – stars: individual: V2069 Cyg (RX J2123.7+4217) – stars: magnetic field – novae, cataclysmic variables – X-rays: binaries.

1 INTRODUCTION

Magnetic cataclysmic variables (CVs) are interacting close binary systems in which material transferred from a Roche lobe filling low-mass companion is accreted by a magnetic white dwarf (WD). Magnetic CVs are subdivided in two groups: polars (or AM Her type) and intermediate polars (IPs; or DQ Herculis type). In polars, the WD has a sufficiently strong magnetic field ($B \sim 10^7–10^8$ G) which locks the system into synchronous rotation ($P_{\text{spin}} = P_{\text{orb}}$) and prevents the accretion disc to form around the WD. In IPs, the field of the WD is one order of magnitude weaker ($B \sim 10^6–10^7$ G), and therefore insufficient to force the WD to spin with the same period as the binary system orbits ($P_{\text{spin}} < P_{\text{orb}}$). The accretion in IPs happens through a disc with a disrupted inner region (Cropper 1990; Patterson 1994; Warner 1995; Hellier 2001).

V2069 Cyg (RX J2123.7+4217) was discovered as a hard X-ray source by Motch et al. (1996) and identified as a CV. Thorstensen & Taylor (2001) reported a most probable orbital period of 0.311683 d (7.48 h) from their spectroscopic observations. de Martino et al. (2009) performed a preliminary analysis of XMM–Newton observations that showed a strong peak at the fundamental frequency of 116.3 cycles d$^{-1}$ and harmonics up to the third in the power spectrum. Additionally, the sinusoidal fit to the profile from both EPIC-pn and EPIC-MOS data revealed a fundamental period of 743.2 ± 0.4 s and a 55 per cent pulsed fraction. They also reported a spectral fit consisting of a 56 eV blackbody (bbody) component plus 16-keV thermal plasma emission and a Gaussian at 6.4-keV emission line with an equivalent width (EW) of 159 eV, being absorbed by a partial (69 per cent) covering model with $N_H = 1.1 \times 10^{23}$ cm$^{-2}$ and a total absorber with $N_H = 5 \times 10^{21}$ cm$^{-2}$. Their spectral analysis confirmed that V2069 Cyg is a hard X-ray-emitting IP with a soft X-ray component. Butters et al. (2011) carried out an analysis of the RXTE data in the 2.0–10.0 keV energy range and found the spin period of the V2069 Cyg WD to be 743.2 ± 0.9 s with a double-peaked modulation. They also reported the spectral results with a 6.4-keV iron line which is typical of IPs.

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2 OBSERVATIONS

2.1 High-time-resolved photometric observations

We performed photometric observations of V2069 Cyg with the Optical Timing Analyzer (OPTIMA) instrument at the 1.3-m telescope at Skinakas Observatory, Crete, Greece. The high-speed photometer OPTIMA is a sensitive, portable detector for observing extremely faint optical pulsars and other highly variable astrophysical sources. The detector contains eight fibre-fed single-photon counting avalanche photo-diodes (APDs), and a Global Positioning System for the time control. Single photons are recorded in all channels with an absolute time-tagging accuracy of \(-4\) μs. The quantum efficiency of the APDs reaches a maximum of 60 per cent at 750 nm and lies above 20 per cent in the range 450–950 nm (Kanbach et al. 2003). To observe V2069 Cyg, OPTIMA was pointed at RA(J2000) = \(21^h23^m44.0^s\) and Dec.(J2000) = \(+42^\circ18^\prime01^\prime\prime\), corresponding to the central aperture of a hexagonal bundle of fibres (Fig. 1). A separate fibre is located at a distance of \(\sim 1\) arcmin as a night sky background monitor. The log of the observations is given in Table 1.

2.2 Swift/XRT observations

The simultaneous soft X-ray observations of V2069 Cyg were performed with the Swift’s X-ray Telescope (XRT; Burrows et al. 2005) in the energy range of 0.3–10 keV. The CCD of the Swift/XRT was operated in the photon-counting mode which retains full imaging and spectroscopic resolution with a time resolution of 2.54 s. The Swift source position is RA(J2000) = \(21^h23^m44.0^s\) and Dec.(J2000) = \(+42^\circ18^\prime01^\prime\prime\), with an error radius of 3.5 arcsec. For the XRT data, we applied the following filters: grade 0–4 and a circular region filter centred at the position of the source with a 10-pixel radius (corresponding to \(\sim 235\) arcsec).

2.3 XMM–Newton observations

The XMM–Newton observation of V2069 Cyg was performed on 2009 April 30 (observation ID: 0601270101). The EPIC instruments were operated in full-frame imaging mode with thin and medium optical blocking filters for EPIC-pn (Strüder et al. 2001) and EPIC-MOS (Turner et al. 2001), respectively. The exposure times were 26433 s for EPIC-pn, 28023 s for EPIC-MOS1 and 28029 s for EPIC-MOS2. We used the XMM–Newton Science Analysis Software (SAS) v.10.0.0 to process the event files. The source coordinates derived from a standard source detection analysis of the combined EPIC images are RA(J2000) = \(21^h23^m44.6^s\) and Dec.(J2000) = \(+42^\circ18^\prime00^\prime.1\). We identified the circular photon extraction regions (with radii of 36, 53 and 56 arcsec for EPIC-pn, EPIC-MOS1 and EPIC-MOS2, respectively) around the source by optimizing the signal-to-noise ratio (S/N). A circular region was used for the background extraction from a nearby source-free area (with a radius of 35 arcsec) on the same CCD as the source. To create spectra, we selected single-pixel events (PATTERN = 0) from the EPIC-pn data and single- to quadruple-pixel events (PATTERN 0–12) from the EPIC-MOS data. For the timing analysis, we used single- and double-pixel events from the EPIC-pn data (PATTERN 0–4) and single- to quadruple-pixel events from the EPIC-MOS data. We sorted out bad CCD pixels and columns (FLAG = 0). After the standard pipeline processing of the EPIC photon event files, we rejected some part of the data which were affected by very high soft proton background. We created good time intervals (GTIs) from background light curves (7.0–15.0 keV band) using count rates below 15 cts ks\(^{-1}\) and 2.5 cts ks\(^{-1}\)arcmin\(^{-2}\) for the EPIC-pn data and 2.5 cts ks\(^{-1}\)arcmin\(^{-2}\) for the MOS data. The spectra of EPIC-pn, EPIC-MOS1 and EPIC-MOS2 contain 10,576, 5908 and 6000 background-subtracted counts, respectively.

3 DATA ANALYSIS

3.1 Timing analysis of the OPTIMA and Swift/XRT data

We analysed the data using the HEASoft analysis package v.6.9. The X-ray and optical photon arrival times were converted to the Solar system barycentre. OPTIMA count rates of the source were obtained from the central fibre (see Fig. 1). Raw data were binned with 1 s, and after ‘flattening’ all fibre channels on a source-free region of the sky background, the corresponding calibrated background counts were subtracted. We chose the fibre number 5 as the best representative of the background, because its APD response was closest to the APD response of channel 0 (Fig. 2).

The resulting photometric light curve shows a prominent periodic variability (Fig. 3). The power spectrum was computed with the fast Fourier transform (FFT) algorithm and normalized such that the white-noise level expected from the data uncertainties corresponds to a power of 2 (Fig. 4). The power spectrum shows peaks at the fundamental spin frequency (first harmonic) 0.00134277 Hz and its second harmonic 0.00268555 Hz (periods of 744.73 and...
Figure 2. OPTIMA light curves of V2069 Cyg from the 2009 July 2 observation (no. 1 in Table 1), shown as raw, uncalibrated count rates binned in 1-s intervals. Source count rates were obtained from the central fibre (channel 0) after subtraction of the properly calibrated sky background trace (channel 5). The sky background decreases in brightness because of the setting Moon.

Figure 3. Light curve of V2069 Cyg as derived in Fig. 2, zoomed in the count rate scale for better visibility. The optical periodicity is clearly visible. The data are background subtracted and binned into 10-s intervals. Time 0 corresponds to MJD = 55014.92172.

Figure 4. Power spectrum obtained from the OPTIMA data (Table 1, all epochs). It shows prominent peaks at the fundamental spin frequency (first harmonic) of 0.00134277 Hz and its second harmonic of 0.00268555 Hz. An instrumental frequency at 0.0371094 Hz is also visible.

Figure 5. The $\chi^2$ periodogram as a function of the period, obtained from the OPTIMA data. The central value (=0) corresponds to the best spin period of 743.38 s.

3.2 Timing analysis of the XMM–Newton data

For the timing analysis of the XMM–Newton data, we corrected the event arrival times to the Solar system barycentre. The background-subtracted X-ray light curves in the 0.2–10.0 keV energy band obtained from the EPIC-pn and combined MOS data with a time binning of 55 s are shown in Fig. 8. The periodic variations around 745 s can be seen clearly in the X-ray light curves. To improve the statistics for timing analysis, a combined EPIC-pn, EPIC-MOS1 and EPIC-MOS2 event list from the source extraction region was created. The FFT timing analysis of the combined X-ray data revealed the presence of four harmonic frequencies with a strong peak at the fundamental frequency of 0.00134277 Hz that corresponds to a period of 744.73 s, as shown in Fig. 9. We found that the fundamental frequency is much stronger than the second harmonic at energies above 0.5 keV, while the second harmonic (with very weak power) is stronger than the fundamental frequency at energies below 0.5 keV. A similar behaviour was also reported by Evans & Hellier (2004) for V405 Aur. To determine the pulse period and its error, we applied the Bayesian formalism as described in Gregory & Loredo (1996). Using the combined and merged EPIC data in the 0.2–10 keV energy band reveals the spin period of the WD as...
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Figure 6. Pulse profile obtained from all OPTIMA data (Table 1, all epochs) folded with the 743.38-s spin cycle (32 bins period$^{-1}$). The profile is background subtracted and normalized to the average count rate of 4621 cts s$^{-1}$. Epoch, MJD = 54951.0.

Figure 7. Pulse profile obtained from the Swift-XRT data (0.3–10.0 keV) folded at 743.38 s (16 bins period$^{-1}$) with an arbitrary zero-point (MJD = 55014.0). The profile is background subtracted and normalized to an average count rate of 0.0918 cts s$^{-1}$.

742.35 ± 0.23 s at 1σ uncertainty. We obtained the optical spin period slightly longer than the X-ray spin period; however, both periods are compatible within their errors.

We folded the light curve to obtain the pulse profiles from the EPIC data (Fig. 10) with the spin period in the different energy bands of 0.2–1.0, 1.0–2.0, 2.0–4.5 and 4.5–10.0 keV and calculated hardness ratios (Fig. 11) as a function of the pulse phase. The hardness ratios were derived from the pulse profiles in two neighbouring standard energy bands \( HR_i = (R_{i+1} - R_i)/(R_{i+1} + R_i) \), where \( R_i \) denotes the background-subtracted count rate in the energy band \( i \), with \( i \) from 1 to 4. The XMM–Newton data also show a double-peaked modulation with a period of 742.35-s consistent with the values obtained from OPTIMA, Swift/XRT and RXTE data. The double-peaked pulse profile is more prominent at lower energies (0.2–0.7 keV), while the second peak is weaker at higher energies (0.7–10.0 keV; see Fig. 12). Here, the second peak is separated by less than half of the pulse cycle, and the power spectrum of the X-ray data is dominated by the fundamental spin frequency (i.e. $1/P_{\text{spin}}$). A similar behaviour was observed in the X-ray data of IP V709 Cas by Norton et al. (1999), where the power spectrum is dominated by the fundamental harmonic. The pulse profiles have highly asymmetrical rise and decay flanks. A dip feature is significant before the primary pulse maximum in the 0.2–1.0 keV band and centred on the primary maximum in the 1.0–2.0 keV band, while the primary maximum is more symmetric at higher energies (Fig. 10). A similar feature was also observed in V709 Cas (de Martino et al. 2001), in NY Lup (Haberl, Motch & Zickgraf 2002) and in UU Col (de Martino et al. 2006b). The evolution of the pulse profiles with double-peaked structure from lower energies to higher causes the variations in the hardness ratios. In Fig. 11, the hardness ratios show a hardening (increase) at spin minimum and a softening (decrease) at spin maximum, which is more prominent in HR3. This typical behaviour is often observed from IPs and is generally produced by the larger photoelectric absorption when viewing along the accretion curtain (de Martino et al. 2001; Haberl et al. 2002). In HR2, the ratio shows two asymmetric maxima, separated by a dip centred on the primary spin maximum seen in the 1.0–2.0 keV band and the second one appearing with a tooth shape produced by the secondary spin maximum (see Fig. 10). In HR1, an anti-phase behaviour is observed with respect to HR2.
3.3 Orbital phase-resolved timing analysis

We investigated if the pulse shape of the rotating WD changes with the orbital phase of the binary system. The orbital phase was determined with the following ephemeris: phase (BJD) = [T – 245 1066.7837(20)]/0.311 683(2), where T is the observation time (Thorstensen & Taylor 2001). For this purpose, we obtained the WD pulse profiles in four orbital phase ranges: 0.0–0.25, 0.25–0.5, 0.5–0.75 and 0.75–1.0. Results are shown in Figs 13 and 14 for OPTIMA and EPIC data, respectively. There is some indication of a profile change, especially in the orbital phase range 0.5–0.75, for both optical and X-ray light curves.

3.4 Spectral analysis of the XMM–Newton data

In order to estimate the basic parameters of the emitting region, a spectral analysis of the X-ray data was performed with XSPEC v.12.5.0x (Arnaud 1996). The three EPIC spectra were fitted simultaneously with a model consisting of thermal plasma emission (MEKAL; Mewe, Gronenschild & van den Oord 1985) and a soft bbody component (as suggested by de Martino et al. 2009), absorbed by a simple photoelectric absorber (phabs) and a partially covering photoelectric absorber (pcfabs). An additional Gaussian line is required which represents iron K fluorescent emission at 6.4 keV, as is often seen from classical IPs. To account for cross-calibration uncertainties, a constant factor was introduced. The absorbers phabs...
Table 2. Spectral fit results for the XMM–Newton EPIC data.

| Model      | Parameter | Unit      | Value    | Error       |
|------------|-----------|-----------|----------|-------------|
|            |           |           |          |             |
| phabs      | NH        | \(10^{21}\) cm\(^{-2}\) | 3.84     | (-0.04, +0.05) |
| pcfabs     | NH        | \(10^{22}\) cm\(^{-2}\) | 8.29     | (-1, +1.2)   |
| MEKAL      | kT        | keV       | 20.0     | Frozen      |
| nH         | cm\(^{-3}\) |           | 1.0      | Frozen      |
| Abundance  |           |           |          |             |
| bbody      | kT        | keV       | 6.29×10\(^{-3}\) | (-2.4, +2.6)×10\(^{-4}\) |
| norm       |           |           | 2.18×10\(^{-4}\) | (-0.75, +1.2)×10\(^{-4}\) |
| gaussian   | LincE     | keV       | 6.385    | ±0.017      |
| Sigma      | eV        |           | 51       | (-32, +27)  |
| norm       |           |           | 2.6×10\(^{-5}\) | (-5.4, +3.9)×10\(^{-6}\) |
| constant factor | pn |           | 1.0      | Frozen      |
| MOS1       |           |           | 1.026    | ±0.018      |
| MOS2       |           |           | 1.028    | ±0.018      |

Figure 15. The composite model \((\text{phabs} \ast \text{pcfabs}) \ast (\text{MEKAL} + \text{bbody} + \text{gaussian}) \ast \text{constant})\) fitted to the spectrum of the EPIC-pn (black) and MOS (green and red) data in the 0.2–10 keV energy band. The bottom panel shows the residuals.

and pcfabs describe the absorptions of the interstellar (along the line of sight) and circumstellar (inside the system by the accretion curtain/stream), respectively (Staude et al. 2008). The MEKAL model produces an emission spectrum from hot diffuse gas above the WD’s surface and includes line emissions from various elements. In a first fit to the spectra, the plasma temperature for the MEKAL component could not be constrained. Therefore, we fixed the plasma temperature at 20 keV, a value typical for IPs (Staude et al. 2008). We obtained a best fit with reduced \(\chi^2\) of 1.002 (\(\chi^2\) of 1014.69 with 1013 degrees of freedom). The spectral parameters for the fit are summarized in Table 2 and the spectra including the best-fitting model are shown in Fig. 15.

We determined the hydrogen column density as \(N_H = 3.84 \times 10^{21} \text{cm}^{-2}\). This is higher than the total Galactic hydrogen column density \((3.79 \times 10^{20} \text{cm}^{-2})\), an interpolated value from Dickey & Lockman 1990 that was calculated using the HEASARC \(N_H\) web interface\(^1\) in the direction of the source. Our result is comparable to the value \((5 \times 10^{21} \text{cm}^{-2})\) obtained by de Martino et al. (2009). For the partial absorber we find, \(N_H = 8.29 \times 10^{22} \text{cm}^{-2}\) with a covering fraction of 0.65. Similar values of the partial absorber were derived for V2069 Cyg (de Martino et al. 2009) and the other soft IPs observed with XMM–Newton (see Table 3). The absorbed flux of V2069 Cyg in the 0.2–10.0 keV energy band (derived for EPIC-pn) is \(7.93 \times 10^{-12} \text{erg cm}^{-2} \text{s}^{-1}\), which corresponds to a source intrinsic flux (with absorption set to 0) of \(2.64 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}\) (EPIC-MOS values are 2 per cent higher corresponding to the constant factors derived from the fit). The spectra around the Fe–K emission line complex are enlarged in Fig. 16. The iron fluorescence and Fe \(\text{XXVI}\) lines are clearly resolved in the EPIC spectra. The Fe \(\text{XXVI}\) line energy identified from the xspec possible lines list

Figure 16. Enlarged part of Fig. 15 showing the Fe line complex in the EPIC spectra.

\(^1\) Available from http://heasarc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl

Table 3. The parameters of the partial absorber obtained for V2069 Cyg and some soft IPs observed with XMM–Newton.

| Source       | \(N_H\) (\(\text{cm}^{-2}\)) | CvrFract | References |
|--------------|------------------------|----------|------------|
| V2069 Cyg    | \(11 \times 10^{22}\)  | 0.69     | 1          |
| MU Cam       | \(7.9 \times 10^{22}\)  | 0.61     | 2          |
| PQ Gem       | \(11.1 \times 10^{22}\) | 0.45     | 3          |
| UU Col       | \(10 \times 10^{22}\)   | 0.51     | 4          |
| V405 Aur     | \(6.1 \times 10^{22}\)  | 0.52     | 5          |
| NY Lup       | \(9.7 \times 10^{22}\)  | 0.47     | 6          |

References. (1) de Martino et al. (2009); (2) Staude et al. (2008); (3) Evans, Hellier & Ramsay (2006); (4) de Martino et al. (2006b); (5) Evans & Hellier (2004); (6) Haberl et al. (2002).
Figure 17. Pulse profiles folded with 743.38 s (20 bins period$^{-1}$) obtained from the combined XMM–Newton EPIC 0.2–10 keV and OPTIMA data. Epoch, MJD = 54951.0.

is $\sim$6.95 keV and the fluorescence line energy derived from the fit is $\sim$6.385 $\pm$ 0.017 keV. The EW of the fluorescent line is 243 eV.

4 DISCUSSION

We have presented the optical (OPTIMA) and X-ray (Swift-XRT and XMM–Newton EPIC) observations of the IP V2069 Cyg. The timing analysis of the optical and X-ray data reveals pulsations at periods of 743.38 \pm 0.25 and 742.35 \pm 0.23 s, respectively, representing the spin period of the WD. We have found that the second harmonic is much stronger than the fundamental in the power spectrum obtained from the optical data. Furthermore, the fundamental frequency from the XMM–Newton data is weak or even absent at energies <0.5 keV, while it is stronger at >0.5 keV, compared to the second harmonic. IP V405 Aur has shown a very similar behaviour in the XMM–Newton data (Evans & Hellier 2004). The double-peaked pulsations at the spin period are clearly observed in the optical and X-ray data (0.2–10 keV). The folded light curves show a more prominent double-peaked pulse profile when the power spectrum is dominated by the second harmonic. When the second harmonic is weak, the curve possesses a similar profile but with a weaker second peak. Therefore, the power spectrum of the optical data is dominated by the second harmonic, while that of the X-ray data is dominated by the fundamental. The peak separation is around 0.5 for the optical data and less than 0.5 for the X-ray data.

IP systems (assuming equilibrium rotation) with a short spin period will have relatively small magnetospheres, corresponding to the shorter Keplerian periods in the inner accretion disc. In such short-period systems, the WD is therefore expected to have a weak magnetic field. Magnetic forces of the WD pick up the material from the accretion disc approximately at the co-rotation radius. The material attaches to the field lines and is channelled on to the WD’s magnetic poles, where it undergoes a strong shock. Thereafter, it settles on the surface and cools by the emission of X-ray bremsstrahlung and optical/infrared cyclotron (Rosen, Mason & Cordova 1988; Norton et al. 2004a). As proposed by Evans & Hellier (2004), most likely the prominent double-peaked modulation in the soft X-ray emission is due to the changing viewing geometry on to the accreting polar caps. We view the heated surface of the WD most favourably when one of the poles points towards us. Nevertheless, due to the highly inclined dipole axis, external regions of the accretion curtains will not quite cross the line of sight; therefore, the hard X-ray emission exhibits double-peaked pulse profiles with a weaker secondary peak. However, the intensity of the pulse profiles could be also affected by the opacity resulting in

Figure 18. The $P_{\text{orb}}$–$P_{\text{spin}}$ diagram of 39 IPs: DP, double-peaked pulsation; SXR, soft X-ray component; discless, have no accretion disc. The vertical dashed lines show the approximate location of the ‘period gap’, and the diagonal lines are for $P_{\text{spin}} = P_{\text{orb}}$ (solid) and $P_{\text{spin}} = 0.1/0.01/0.001 \times P_{\text{orb}}$ (dashed). V2069 Cyg (shown with a star) is located well within the population of double-peaked IPs with a soft X-ray component but has a rather low spin-orbit period ratio of 0.0276.

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### Table 4. 39 IPs with known spin and orbital periods.

| Name          | $P_{\text{orb}}$ (h) | $P_{\text{spin}}$ (s) | $P_{\text{spin}}/P_{\text{orb}}$ | Properties$^a$ | Period references$^b$ |
|---------------|----------------------|------------------------|-----------------------------------|-----------------|-----------------------|
| V709 Cas      | 5.341                | 312.780                | 0.01627                           | DP              | 33, 41                |
| NY Lup        | 9.870                | 693.010                | 0.01950                           | SXR             | 2, 21, 17, 41         |
| RKS J213344.1+510725 | 7.193            | 570.800                | 0.02204                           | SXR             | 2, 11, 42             |
| Swift J0732.5−1331 | 5.604            | 512.420                | 0.02540                           | –               | 5, 41                 |
| V2069 Cyg     | 7.480                | 743.384                | 0.02756                           | SXR, DP         | 18, 41                |
| RKS J070407.9−262501 | 4.380            | 480.670                | 0.03205                           | SXR             | 2, 22, 44             |
| El Uma        | 6.430                | 741.660                | 0.03204                           | –               | 3                     |
| V405 Aur      | 4.160                | 545.456                | 0.03642                           | SXR, DP         | 2, 20, 23, 41         |
| NY Lup        | 9.870                | 809.700                | 0.03819                           | –               | 12, 41                |
| IGR 00234+6141 | 4.033          | 563.500                | 0.03881                           | –               | 6                     |
| RKS J165443.5−191620 | 3.700             | 546.000                | 0.04099                           | –               | 40                    |
| Swift J0732.5−1331 | 5.604            | 512.420                | 0.02540                           | –               | 5, 41                 |
| V2069 Cyg     | 7.480                | 743.384                | 0.02756                           | SXR, DP         | 18, 41                |
| RXS J070407.9−262501 | 4.380            | 480.670                | 0.03205                           | SXR             | 2, 22, 44             |
| El Uma        | 6.430                | 741.660                | 0.03204                           | –               | 3                     |
| V405 Aur      | 4.160                | 545.456                | 0.03642                           | SXR, DP         | 2, 20, 23, 41         |
| NY Lup        | 9.870                | 809.700                | 0.03819                           | –               | 12, 41                |
| IGR 00234+6141 | 4.033          | 563.500                | 0.03881                           | –               | 6                     |
| RKS J165443.5−191620 | 3.700             | 546.000                | 0.04099                           | –               | 40                    |
| Swift J0732.5−1331 | 5.604            | 512.420                | 0.02540                           | –               | 5, 41                 |
| V2069 Cyg     | 7.480                | 743.384                | 0.02756                           | SXR, DP         | 18, 41                |
| RXS J070407.9−262501 | 4.380            | 480.670                | 0.03205                           | SXR             | 2, 22, 44             |
| El Uma        | 6.430                | 741.660                | 0.03204                           | –               | 3                     |
| V405 Aur      | 4.160                | 545.456                | 0.03642                           | SXR, DP         | 2, 20, 23, 41         |
| NY Lup        | 9.870                | 809.700                | 0.03819                           | –               | 12, 41                |
| IGR 00234+6141 | 4.033          | 563.500                | 0.03881                           | –               | 6                     |
| RKS J165443.5−191620 | 3.700             | 546.000                | 0.04099                           | –               | 40                    |
| Swift J0732.5−1331 | 5.604            | 512.420                | 0.02540                           | –               | 5, 41                 |
| V2069 Cyg     | 7.480                | 743.384                | 0.02756                           | SXR, DP         | 18, 41                |
| RXS J070407.9−262501 | 4.380            | 480.670                | 0.03205                           | SXR             | 2, 22, 44             |
| El Uma        | 6.430                | 741.660                | 0.03204                           | –               | 3                     |
| V405 Aur      | 4.160                | 545.456                | 0.03642                           | SXR, DP         | 2, 20, 23, 41         |

$^a$SXR: soft X-ray bbody components; DP: double-peaked pulse profiles.

$^b$References. (1) Allan, Hellier & Beardmore (1998); (2) Anzolin et al. (2008); (3) Baskill, Wheatley & Osborne (2005); (4) Kim et al. (2005); (5) Butters et al. (2007); (6) Bonnet-Bidaud et al. (2007); (7) Bonnet-Bidaud, de Martino & Mouchet (2009); (8) Buckley et al. (1995); (9) Burwitz et al. (1996); (10) Butters et al. (2008); (11) Butters et al. (2009a); (12) Butters et al. (2009b); (13) Choi, Dotani & Agrawal (1999); (14) Crampton, Fisher & Cowley (1986); (15) de Martino et al. (2008); (16) de Martino et al. (1999); (17) de Martino et al. (2006a); (18) de Martino et al. (2009); (19) Duck et al. (1994); (20) Evans & Hellier (2004); (21) Evans & Hellier (2007); (22) G"ansicke et al. (2005); (23) Harlaftis & Horne (1999); (24) Haswell et al. (1997); (25) Hilton et al. (2009); (26) Hellier (2007); (27) Hellier, Ramseyer & Jablonski (1994); (28) Hellier, Mukai & Beardmore (1997); (29) Hellier, Wynn & Buckley (2002a); (30) Hellier, Beardmore & Mukai (2002b); (31) Kemp et al. (2002); (32) Mauche (2004); (33) Norton et al. (1999); (34) Norton et al. (2002); (35) Patterson et al. (2004); (36) Pretorius (2009); (37) Hellier, Beardmore & Buckley (1998); (38) Staubert et al. (2003); (39) Schlegel (2005); (40) Scaringi et al. (2011); (41) Scaringi et al. (2010); (42) Thorstensen, Peters & Skinner (2010); (43) de Martino et al. (2006b); (44) Patterson et al. (2011); (45) Zhang et al. (1995).
electron scattering and absorption in the highly ionized post-shock region, or an offset of the magnetic axis from the WD centre (Allan et al. 1996; Norton et al. 1999; Evans & Hellier 2004).

The pulse profiles of the optical and X-ray data (each folded with both 742.35- and 743.38-s spin period and the same reference time) are out of phase. As an example, we show these profiles folded with 743.38 s in Fig. 17. de Martino et al. (2009) also reported that X-ray pulses (from EPIC-pn) are anti-phased with the optical pulses (in the B band from an optical monitor on the XMM–Newton). X-ray and optical/infrared photons in some IPs originate from two different regions. The optical/infrared photons are thought to originate in the X-ray-heated magnetic polar caps and possibly in the accretion stream (Eracleous et al. 1994; Israel et al. 2003; Revnivtsev et al. 2010). Norton, Haswell & Wynn (2004b) suggested that one of the magnetic poles heated by the accretion flow will leave behind a heated trail on the WD surface which will emit optical/infrared photons. During the emission, some part of the optical/infrared photons will be absorbed by the flow while the accretion flow is heating the second pole. At that time, the remaining optical/infrared modulations will be seen, which are shifted with respect to the X-rays. The phase shift observed between the optical and X-ray pulse profiles in V2069 Cyg is most probably caused by this X-ray-heated mechanism.

On the other hand, Norton et al. (1999) suggested that IPs that show a single-peaked pulse profile resulting from stream-fed (or disc-overflow) accretion are an indicator of a WD with a relatively strong magnetic field. These IPs with long WD spin periods (>700 s) might show X-ray beat periods (1/\(P_{\text{beat}} = 1/\left( P_{\text{spin}} - 1/\left(P_{\text{orb}}\right)\right)\) at some time in their lives (FO Aqr, TX Col, BG CMi, AO Psc, V1223 Sgr and RX J1712.6–2414). In contrast, IPs with short WD spin periods (<550 s) have shown double-peaked pulse profiles and must therefore have weak magnetic fields. These short-period systems did not exhibit X-ray beat periods (AE Aqr, DQ Her, XY Ari, V709 Cas, GK Per, YY Dra and V405 Aur). In the power spectrum of V2069 Cyg, we have not found any specific signal at the beat frequency. This absence indicates that in these short-period IPs and V2069 Cyg accretion does not occur in a stream-fed or disc-overflow scenario (Norton et al. 1999).

The X-ray spectra of V2069 Cyg can be described by thermal plasma emission (\(kT\) of ~20 keV) plus a soft bbody component with complex absorption and an additional fluorescent iron K emission line, which originates on the WD surface (at 6.4 keV, with an EW of 243 eV). V2069 Cyg and V405 Aur show similar bbody parameters with \(kT\) of ~77 and ~40 eV (Evans & Hellier 2004), respectively. Moreover, the two IPs have quite similar spin-orbit period ratios of 0.0276 for V2069 Cyg (743.38 s/26928 s) and 0.036 for V405 Aur (545.5 s/14986 s).

We adopted Mukai's classification of IPs and updated his \(P_{\text{spin}}/P_{\text{orb}}\) diagram to include V2069 Cyg (see Fig. 18 and Table 4). Several IPs are found close to \(P_{\text{spin}}/P_{\text{orb}} = 0.1\). There are 28 systems in the range of 0.01 < \(P_{\text{spin}}/P_{\text{orb}}\) ≤ 0.1 and \(P_{\text{orb}} > 3\) h, five systems with \(P_{\text{spin}}/P_{\text{orb}}\) ≥ 0.1 and \(P_{\text{orb}} < 2\) h, and only one system with \(P_{\text{spin}}/P_{\text{orb}} \sim 0.049\) that lies in the 'period gap'. Finally, there are five systems with \(P_{\text{spin}}/P_{\text{orb}} < 0.01\), which are defined as fast rotating WDs. Only one of them, AE Aqr, shows propeller behaviour. They also show the soft X-ray bbody component in their spectrum (Norton, Sommerscales & Wynn 2004c; Parker, Norton & Mukai 2005; Evans & Hellier 2007; Norton & Mukai 2007; Anzolin et al. 2008).


c2 Available from http://asd.gsfc.nasa.gov/Koji.Mukai/iphome/iphome.html

5 CONCLUSIONS

We conclude that V2069 Cyg is an example of an IP that shows double-peaked emission profiles at the WD spin period which are probably caused by a weak magnetic field, in a WD with short spin period. The X-ray spectrum shows a soft bbody component and thermal plasma emission and its X-ray and optical emission have a double-peaked modulation. We performed simultaneous optical/ X-ray observations of V2069 Cyg to search for any delays between these two energy bands. However, the low count rates in the Swift data did not allow us to constrain these delays.

ACKNOWLEDGMENTS

IN acknowledges support from the EU FP6 Transfer of Knowledge Project ‘Astrophysics of Neutron Stars’ (MKTD-CT-2006-042722). AS acknowledges support from grant N203 387737 of the Polish Ministry of Science and Higher Education, as well as grant FNP HOM/2009/11B and the EU grant PERG05-GA-2009-249168. GK acknowledges support from the EU FP6 Transfer of Knowledge Project ASTROCENTER (MKTD-CT-2006-039965) and the kind hospitality of the Skinakas team at University of Crete. We acknowledge the use of public data from the Swift data archive. We thank Aysun Akyuz and Arne Rau for discussions on this paper, as well as Anna Zajczyk (CAMK) and Andrzej Szary (UZG) for their help with observations. We also thank the Skinakas Observatory for their support and allocation of telescope time. Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology, Hellas, and the Max Planck Institute for Extraterrestrial Physics.

REFERENCES

Allan A., Horne K., Hellier C., Mukai K., Burwig H., Bennie P. J., Hilditch R. W., 1996, MNRAS, 279, 1345
Allan A., Hellier C., Beardmore A., 1998, MNRAS, 295, 167
Anzolin G., de Martino D., Bonnet-Bidaud J.-M., Mouchet M., Günsicke B. T., Matt G., Mukai K., 2008, A&A, 489, 1243
Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, ASP Conf. Ser. Vol. 101, Astronomical Data Analysis Software and Systems V. Astron. Soc. Pac., San Francisco, p. 17
Baskill D. S., Wheatley P. J., Osborne J. P., 2005, MNRAS, 357, 626
Bonnet-Bidaud J. M., de Martino D., Falanga M., Mouchet M., Masetti N., 2007, A&A, 473, 185
Bonnet-Bidaud J. M., de Martino D., Mouchet M., 2009, Astron. Telegram, 1895, 1
Buckley D. A. H., Sekiguchi K., Motch C., O’Donoghue D., Chen A.-L., Schwarzenberg-Czerny A., Pietsch W., Harrop-Allin M. K., 1995, MNRAS, 275, 1028
Burrows D. N. et al., 2005, Space Sci. Rev., 120, 165
Burwitz V., Reinsch K., Beuermann K., Thomas H.-C., 1996, A&A, 310, L25
Butters O. W., Barlow E. J., Norton A. J., Mukai K., 2007, A&A, 475, L29
Butters O. W., Norton A. J., Hakala P., Mukai K., Barlow E. J., 2008, A&A, 487, 271
Butters O. W., Katajainen S., Norton A. J., Lehto H. J., Piirola V., 2009a, A&A, 496, 891
Butters O. W., Norton A. J., Mukai K., Barlow E. J., 2009b, A&A, 498, L17
Butters O. W., Norton A. J., Mukai K., Tomskick J. A., 2011, A&A, 526, A77
Choi C.-S., Dotani T., Agrawal P. C., 1999, ApJ, 525, 399
Cropper M., 1990, Space Sci. Rev., 54, 195
de Martino D., Silvotti R., Buckley D. A. H., Günsicke B. T., Mouchet M., Mukai K., Rosen S. R., 1999, A&A, 350, 517
de Martino D. et al., 2001, A&A, 377, 499

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