

# The defining characteristics of Intermediate Polars – the case of three candidate systems

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## ABSTRACT

Intermediate Polars (IPs) are a group of cataclysmic variables (CVs) which are thought to contain white dwarfs which have a magnetic field strength in the range  $\sim 0.1\text{--}10\text{MG}$ . A significant fraction of the X-ray sources detected in recent deep surveys has been postulated to consist of IPs. Until now two of the defining characteristics of IPs have been the presence of high (and complex) absorption in their X-ray spectra and the presence of a stable modulation in the X-ray light curve which is a signature of the spin period, or the beat period, of the accreting white dwarf. Three CVs, V426 Oph, EI UMa and LS Peg, have characteristics which are similar to IPs. However, there has been only tentative evidence for a coherent period in their X-ray light curve. We present the results of a search for coherent periods in *XMM-Newton* data of these sources using an auto-regressive analysis which models the effects of red-noise. We confirm the detection of a  $\sim 760$  sec period in the soft X-ray light curve of EI UMa reported by Reimer et al and agree that this represents the spin period. We also find evidence for peaks in the power spectrum of each source in the range 100–200 sec which are just above the  $3\sigma$  confidence level. We do not believe that they represent genuine coherent modulations. However, their X-ray spectra are very similar to those of known IPs. We believe that all three CVs are *bona fide* IPs. We speculate that V426 Oph and LS Peg do not show evidence for a spin period since they have closely aligned magnetic and spin axes. We discuss the implications that this has for the defining characteristics of IPs.

**Key words:** Stars: binary - close; novae - cataclysmic variables; individual: - EI UMa, LS Peg, V426 Oph; X-rays: binaries

## 1 INTRODUCTION

Cataclysmic Variables (CVs) are interacting binaries in which a white dwarf accretes material from a red dwarf secondary star through Roche lobe over-flow. The majority of CVs accrete via an accretion disc, with the flow forming a strong shock at some height above the photosphere of the white dwarf: this results in the emission of X-rays. For those white dwarfs which have a magnetic field strength above  $\sim 10$  MG (the *polars* or *AM Her stars*), the field is strong enough to prevent the formation of an accretion disc and the accretion flow gets directed towards its magnetic poles. The high field also locks the rotation rate of the white dwarf to the binary orbital period. For those systems with a magnetic field strength between  $\sim 0.1\text{--}10\text{MG}$  the accretion disc gets

disrupted at some distance from the white dwarf: these are called the *Intermediate Polars* (IPs).

Patterson (1994) reviewed the properties of then known IPs and noted six which gave ‘significant clues’ as to their IP nature. These include a stable modulation in the optical and X-ray light curves which is close to, or at, the spin period of the accreting white dwarf ( $P_{spin}$ ); typically  $P_{spin} < P_{orb}$ ; a side-band period which results from a beat between  $P_{spin}$  and  $P_{orb}$ ; and a hard X-ray spectrum which shows evidence of strong (and complex) absorption. One further X-ray property is the presence of strong Fe K $\alpha$  emission (Norton, Watson & King 1991).

At present only a relatively small number of IPs have been fully identified. Patterson (1994) noted 18 *bona fide*

Target	Date	MOS1 Mode	MOS2 Mode	pn Mode	Duration (sec)	Count Rate (Ct/s)
EI UMa	2002-11-02	lw	sw	ff	8246	6.6
LS Peg	2005-06-08	lw	lw	ff	42535	0.70
V426 Oph	2006-03-04	lw	sw	sw	35964	5.5

**Table 1.** The log for the observations of EI UMa, LS Peg and V426 Oph made using *XMM-Newton*. We show the mode the detector was in where ‘sw’ refers to ‘small window’, ‘lw’ large window, ‘ff’ to ‘full frame’. The duration of the observation refers to that using the EPIC pn detector, while the Count Rate is determined over the 0.15–10keV energy range.

IPs, while Koji Mukai’s IP homepage<sup>1</sup> catalogues 29 confirmed IPs. However, there is some evidence that IPs are much more common than these numbers suggest. For instance, deep X-ray observations of the Galactic centre using *Chandra* led to the discovery of a substantial population of hard X-ray sources which Munro et al (2004) suggest are IPs.

It is therefore important to fully characterise the global properties of the nearby CVs. Part of the difficulty lies in classifying CVs, with individual systems showing characteristics of various sub-classes of CV. Baskill, Wheatley & Osborne (2005) performed a systematic analysis of all the non-magnetic CVs observed using *ASCA*. They identified two systems, LS Peg, V426 Oph, which showed X-ray spectra which were significantly more absorbed than the other CVs in their sample. They also identified three systems, the previously noted and EI UMa, which showed evidence for a periodicity in their X-ray light curves (EI UMa also showed high absorption in its X-ray spectrum).

Baskill et al (2005) suggested that EI UMa, LS Peg and V426 Oph were IPs. However, given the rather tentative nature of the periods which they identified, further longer X-ray observations were required to fully class these systems as *bona fide* IPs. We have therefore obtained *XMM-Newton* data of LS Peg and V426 Oph – observations of EI UMa had already been performed in Nov 2002. We present an analysis of these *XMM-Newton* data and discuss the nature of these systems and how this affects the defining characteristics of IPs. (A preliminary analysis of the LS Peg data was presented by Baskill & Wheatley 2006, while Reimer et al 2008 report a period in the soft X-ray *XMM-Newton* data of EI UMa at  $\sim 745$  sec).

## 2 OBSERVATIONS

Observations were carried out using *XMM-Newton* – a log of the observations is shown in Table 1. The EPIC X-ray detectors (MOS, Turner et al 2001; pn, Strüder et al 2001) are relatively wide-field instruments with medium spectral resolution. We do not discuss the RGS detector data, with its higher X-ray spectral resolution capability, nor do we discuss the observations made using the Optical Monitor, since we are mainly concerned with X-ray timing properties. Observations were also carried out of EI UMa in May 2002 but were affected by high background radiation.

The data were reduced using *SAS* v7.1. Only X-ray events which were graded as PATTERN=0-4 and FLAG=0 were used. Events were extracted from a circular aperture centred

on the source, with background events being extracted from a source free area. The background data were scaled to give the same area as the source extraction area and subtracted from the source area. In the case of EI UMa, the events in the EPIC pn detector (which was in full-frame mode) were slightly piled-up during the time intervals which had the greatest count rate. Since the MOS detectors were operating in small window mode, the MOS data were not piled-up. For both LS Peg and V426 Oph we combined the light curves from the two EPIC MOS detectors and compared the results obtained from the EPIC pn detector. We note that in the case of LS Peg there was significantly enhanced background 12–20 ksec from the start of the observation.

## 3 LIGHT CURVES

We show the soft (0.3–2 keV) and hard (2–12keV) light curves of EI UMa, LS Peg and V426 Oph in Figure 1. There is clear evidence for variability in each of the light curves, although none show variability on an obviously coherent timescale. V426 Oph shows large variations in intensity on various timescales, particularly in the soft X-ray band. The fact that the modulation in harder X-rays is not as prominent suggests the soft X-ray variability is due to variation in the absorption. In contrast, LS Peg shows less variability in soft X-rays compared to hard X-rays.

To search for evidence of periodic modulation in the light curves we used the standard Lomb-Scargle power spectrum analysis. We show the power spectra for the soft and hard X-ray light curves in Figure 2. For light curves which are dominated by red noise (noise dominated by low frequencies) non-standard techniques must be used to determine the significance of peaks in the power spectra (which could be due to red noise rather than strict coherent modulations). We used the novel auto-regressive technique described in Hakala et al (2004). Here we fitted a second order auto-regressive model to the data (ie AR(2)). The fitted model is then used to simulate 10000 light curves, which were in turn used to estimate the confidence limits. We superpose the 95.2% ( $2\sigma$ ), 99.7% ( $3\sigma$ ) and 99.95% ( $4\sigma$ ) confidence limits on the power spectra of each light curve in Figure 2.

LS Peg shows a significant peak in its soft X-ray power spectrum which corresponds to its orbital period (4.2 hrs). V426 Oph also shows a peak in the soft X-ray power spectrum (6 hr) which is close to the orbital period (6.85 hrs) and an additional peak (in both soft and hard X-rays) at 3hrs. The orbital period of EI UMa (6.4 hrs) is significantly longer than the duration of the observation. (Those ‘long’ periods are not shown in Figure 2 since we are searching for the

<sup>1</sup> <http://asd.gsfc.nasa.gov/Koji.Mukai/iphome/iphome.html>

Target	Period		Ref
EI UMa	6.4 hrs	Orbital	1
	12.4 min	X-rays	2,3
	12.4–13.6 min	Optical	3
LS Peg	4.2 hrs	Orbital	4
	19 min	Optical	5
	29.6 min	Circ Pol	6
	30.9 min	X-rays	2
V426 Oph	6.85 hrs	Orbital	7
	:2.5, 4.5 or 12.5 hr	X-rays	8
	28 min	X-rays	9
	29.2 min	X-rays	2
	2.1, 4.2 hrs	X-rays	10

**Table 2.** Previously reported periods in V426 Oph, LS Peg and EI UMa. References: (1) Thorstensen (1986), (2) Baskill et al (2005), (3) Reimer et al (2008), (4) Taylor, Thorstensen & Patterson (1999), (5) Szkody et al (2001), (6) Rodriguez-Gil et al (2001), (7) Hessman (1988), (8) Rosen et al (1994), (9) Szkody et al (1990), (10) Homer et al (2004).

shorter period modulations). In addition to these periods, there are several peaks above the  $3\sigma$  confidence level, but only one short period peak above the  $4\sigma$  level, at  $758 \pm 6$  sec period in the 0.3–2 keV band light curve of EI UMa. (This peak is also seen in the EPIC pn light curve which is piled-up to some extent). There is no evidence for this period in the 2–12 keV light curve, although there is a period of  $\sim 250$  sec in this higher energy power spectrum which has a significance of  $\sim 3.7\sigma$ . As noted by Reimer et al (2008) the X-ray period is consistent with their detection of an optical period in the  $U$  band at 747 sec. Reimer et al also report the detection of other periods between 760–770 sec which they take to be the beat period between the orbital period and the spin period.

As the computed confidence limits correspond to the limits at individual periods, there are bound to be some peaks above the  $3\sigma$  limit (1/370 probability) in the power spectra with hundreds of independent frequencies – this is indeed the case. In the case of V426 Oph and LS Peg, none of the peaks with significance between 3– $4\sigma$  coincide with any previously reported periods, nor were they seen in the power spectra derived using the other EPIC instrument. We do not believe that these short period peaks represent a genuine coherent modulation and therefore they do not represent the spin period of the white dwarf.

#### 4 SPECTRA

We give a brief overview of the characteristics of the *XMM-Newton* spectra of our three sources. Detailed spectral fits to the *XMM-Newton* of EI UMa has already been presented by Pandel et al (2005). They found that good fits were only achieved using a complex absorption model (ie a partial covering or an ionised absorption component was required in addition to a single neutral absorption component). Further, the column density of the partial covering absorption model was high,  $N_H \sim 3 \times 10^{22}$  cm $^{-2}$ , and a covering fraction  $\sim 0.4$ – $0.5$ . In contrast, the other non-magnetic CVs in

the sample of Pandel et al (2005) had a neutral absorption column of a few  $\times 10^{20}$  cm $^{-2}$ .

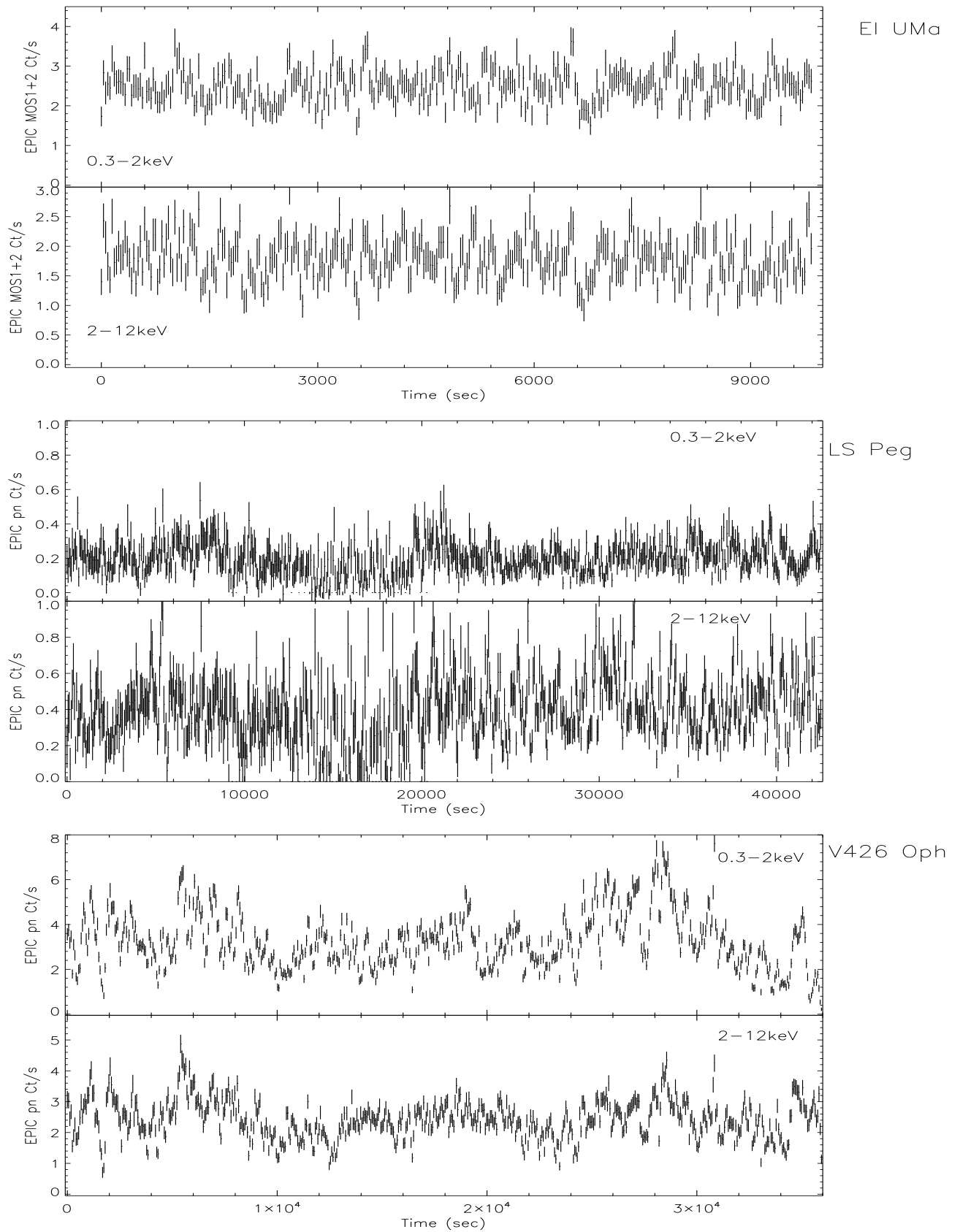
We show in Table 3 the spectral parameters for all three systems and we show the goodness of fit using a simple neutral absorption component and also where we have added a partial covering model. We used the `tbabs` neutral absorption model as used in `XSPEC` and also `cemek1` which is a multi-temperature thermal plasma model. We fitted the integrated X-ray spectrum and have not attempted to determine if there is spectral variability over the course of the orbital period – which is likely to be the case. We stress these are not definitive spectral fits for these objects – rather we make the point that their X-ray spectra require complex absorption components (as in the case of IPs) and their total absorption column density is high compared to the non-magnetic (non-eclipsing) dwarf novae.

We also show the equivalent width of the Fe  $K\alpha$  line-complex at 6.4keV (due to fluorescence),  $\sim 6.65$  keV (the He-like line) and  $\sim 6.95$  keV (the H-like line) in Table 3. (The spectral resolution of the EPIC detectors are not high enough to resolve the He-like line into its three intrinsic components). We measured the equivalent width by fitting an absorbed power law plus 3 Gaussian components over the energy range 4–10 keV. While we stress that these line results are intended to be informative rather than definitive, the He-like line in all three systems show an equivalent width of  $\sim 200$ – $500$  eV. Both non-magnetic CVs (eg Rana et al 2006) and IPs (eg Hellier & Mukai 2004) typically show He-like lines with equivalent widths of several 100 eV so their presence in our sources is not conclusive either way.

#### 5 IS THERE EVIDENCE FOR THE SPIN PERIOD IN EI UMA, LS PEG AND V426 OPH?

Patterson (1994) showed that many IPs had  $P_{spin} \sim 0.1P_{orb}$ . This relationship predicts spin periods for our sources between  $\sim 1500$ – $2500$  sec. However, the current sample of IPs shows a wide spread in  $P_{spin}/P_{orb}$  – see Figure 5 of Norton et al (2008). Our *XMM-Newton* light curves have allowed us to sample very low values of  $P_{spin}/P_{orb}$  (since our timebins can be of short duration). The limiting factor for higher values of  $P_{spin}/P_{orb}$  is set by the time duration of the light curves.

Our red-noise analysis shows periods between 100–200 sec in the X-ray light curves of each of our sources at a significance level just greater than the  $3\sigma$  level. None of these periods have been detected in previous X-ray data. On the other hand, apart from the signature of the orbital periods and the 760 sec modulation in the soft X-ray band of EI UMa reported by Baskill et al (2005) and Reimer et al (2008), none of the previously reported periods (Table 2) were detected. For V426 Oph and LS Peg which were observed for longer than 35 ksec we find no evidence for a spin period between a few 100 sec and  $\sim 10$  ksec. In the case of EI UMa our light curve is 8.2 ksec in duration so therefore cannot rule out the presence of a period greater than this.



**Figure 1.** From the top, the light curves of EI UMa (30 sec bins), LS Peg and V426 Oph (60 sec bins). We show the soft (0.3–2 keV) and hard X-ray (2–12 keV) light curves. In the observation of LS Peg the particle/solar background was high between  $\sim 12$ –20 ksec.

Target	Single Absorber ( $\chi^2_\nu$ , dof)	$N_H$ $\text{cm}^{-2}$	Multi Absorber ( $\chi^2_\nu$ , dof)	$N_H$ $\text{cm}^{-2}$	$N_H$ $\text{cm}^{-2}$	cvf	6.4keV (eV)	6.67keV (eV)	6.95keV (eV)
EI UMa	3.60 (215)	$1.0 \times 10^{20}$	1.80 (213)	$1.0 \times 10^{20}$	$4.5 \times 10^{22}$	0.67	77	256	
LS Peg	11.36 (444)	$2.2 \times 10^{21}$	1.37 (441)	$1.7 \times 10^{21}$	$5.7 \times 10^{21}$	0.91	118	478	86
V426 Oph	2.06 (530)	$1.8 \times 10^{21}$	1.29 (528)	$1.0 \times 10^{21}$	$6.4 \times 10^{21}$	0.65	34	302	153

**Table 3.** The best spectral fits to the *XMM-Newton* EPIC spectra of our three targets. We show the goodness of fit using a single neutral absorption model and a neutral absorption component plus a partial covering model (cvf). We used a multi-temperature thermal plasma model and the emission model.

## 6 THE NATURE OF EI UMA, LS PEG AND V426 OPH

Hellier et al (1990) discussed the possibility of V426 Oph being an IP and concluded it was not since there was no prominent X-ray modulation. In the case of LS Peg, the fact that there is some evidence that its optical flux is circularly polarised (albeit only at a significance level of  $3\sigma$ ) on a period of 29 min hints at a magnetic nature (Rodriguez-Gil et al 2001). Indeed, a number of other IPs show a modulation in the optical circular polarisation at the spin period (see the Katajainen et al 2007 for a recent reference list). It is clear that there is a great deal of uncertainty as to the subtype of V426 Oph and LS Peg. For instance, in the catalogue of Ritter & Kolb (2003), LS Peg is classed as an nova-like, while VY Scl, SW Sex and IP! In the case of EI UMa both Pandel et al (2005) and Reimer et al (2008) suggest it is an IP.

We believe that the fact that all three systems show high levels of complex absorption (ie an equivalent column density  $> 5 \times 10^{21} \text{ cm}^{-2}$ , Table 3) point to these systems being *bona fide* IPs. We now address why they do not show evidence for a spin period in X-rays.

## 7 THE DEFINING CHARACTERISTICS OF IPS

A strong X-ray modulation has always been taken as one of the main defining characteristics of an IP. A modulation at the spin period arises due to phase-varying photoelectric absorption in the accretion column and/or self occultation by the body of the white dwarf. A similar modulation at the beat period arises due to the accretion stream flipping between the poles. However, these modulations will only arise if the magnetic axis of the white dwarf is mis-aligned with the white dwarf spin axis (eg King & Shaviv 1984). Therefore, for all confirmed IPs, it is most likely that the magnetic and spin axes are offset from each other, typically by  $\sim 10$ 's of degrees. Only in one IP (XY Ari) is there an observational measurement of this offset: Hellier (1997) estimates that in XY Ari the magnetic dipole axis is offset from the spin axis by  $8\text{--}27^\circ$  and that the main accretion region is offset from the magnetic axis by a further  $19^\circ$ .

If the magnetic and spin axes of a white dwarf in an accreting binary system are closely aligned, then a disc-fed system will give rise to circular accretion curtains above each magnetic pole (extending to all azimuths). There will essentially be no phase varying photoelectric absorption and no variation in self occultation, and consequently the X-ray signal will show no variation with spin phase. Similarly, in a

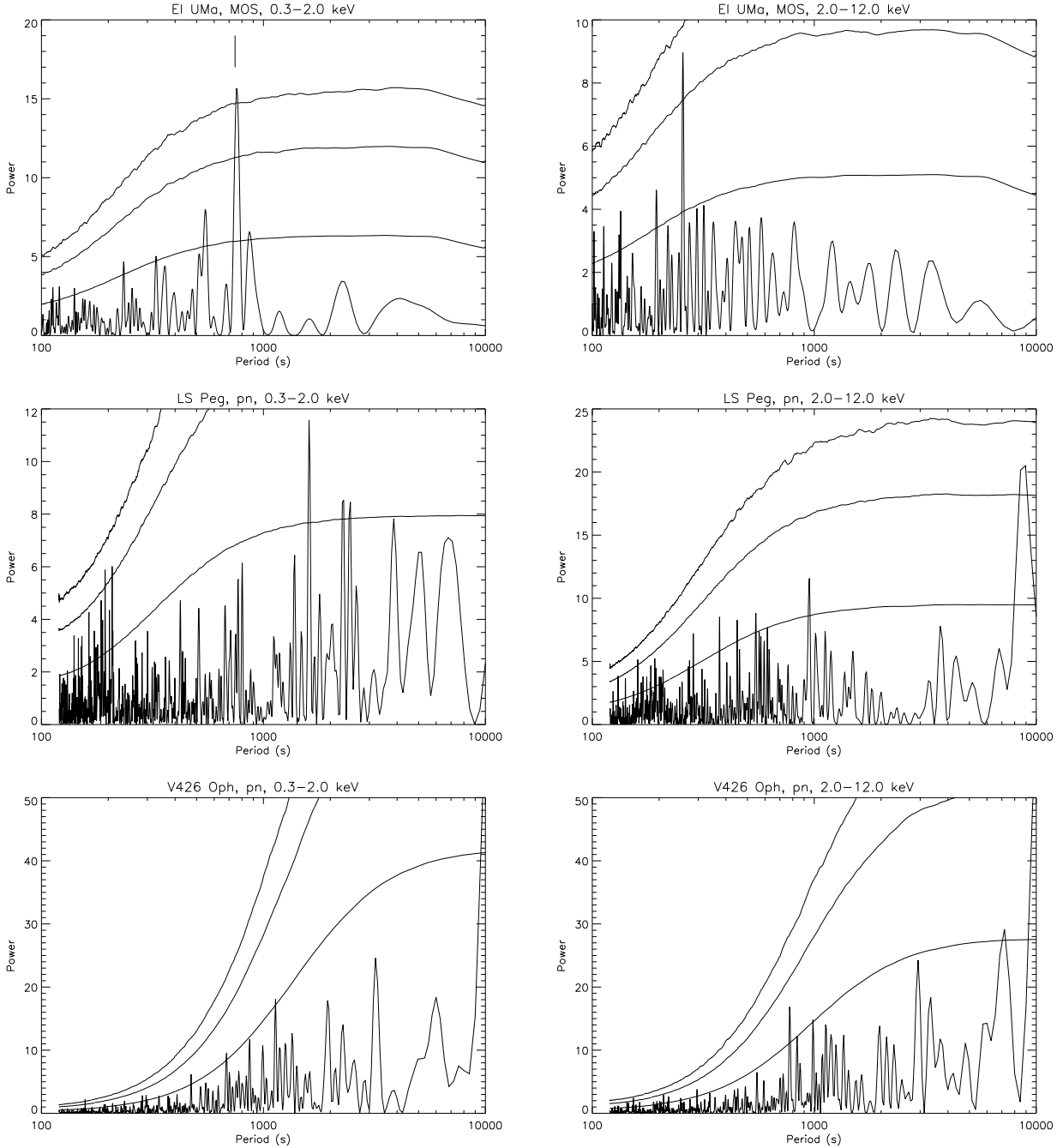
stream-fed system with co-aligned magnetic and spin axes, equal amounts of material are likely to feed onto each pole at all times, and there will be no variation in X-ray flux with beat phase. Axes that are aligned to within a few degrees will likely give rise to an X-ray modulation of less than a few percent depth, which would be undetectable in most cases due to intrinsic X-ray flickering. In contrast, simulations made using the polarisation models of Potter, Hakala & Cropper (1998) show that a mis-alignment between the spin and magnetic axes of even  $5^\circ$  (and assuming accretion onto a small spot at the magnetic poles) gives rise to a modulation in the circular polarisation flux as seen in LS Peg.

We therefore suggest that there should exist a population of IPs with closely aligned spin and magnetic axes which do not show any detectable spin or beat modulation in their X-ray flux. Should such systems exhibit any other defining variation in their X-ray flux?

Up to half of all confirmed IPs also show an X-ray modulation at the system orbital period (Parker, Norton & Mukai 2005). This is presumed to be due to absorption in material at the edge of the accretion disc, thrown up by the impact of the accretion stream. Since  $\sim 50\%$  of all known systems show this effect, and assuming their orbital planes to be randomly orientated with respect to our line of sight, this indicates that the absorbing material must extend far enough out of the orbital plane to be seen at all inclination angles above  $60^\circ$ . The question arises therefore, should not half of the IPs with aligned spin and magnetic axes show such an orbital modulation and be detected that way?

Norton & Mukai (2007) showed that the IP XY Ari exhibits a broad X-ray modulation at its orbital period which comes and goes on a timescale of  $\sim$ months. They interpreted this as evidence for a precessing, tilted or warped accretion disc in that system. They further suggested that such discs may exist in all IPs and that the cause of the warp may be related to the spinning magnetic field anchored to the white dwarf at its centre. A tilted magnetic dipole will stir up the inner edge of the accretion disc and lift material away from the orbital plane, thus initiating the precessing warp or tilt. The lifting of material far enough out of the orbital plane to cause an X-ray orbital modulation in half the known IPs is therefore due to this warp or tilt in the disc, which in turn is due to the tilted dipole at its centre, caused by mis-aligned spin and magnetic axes.

For IPs with closely aligned spin and magnetic axes, the situation is less clear. However, we suggest that for these systems, material is azimuthally concentrated at the point where the accretion stream from the secondary star meets the accretion disc, thereby giving rise to a modulation at the orbital period. Closer to the white dwarf, the accretion



**Figure 2.** From the top, the amplitude spectra of the soft (left hand panels) and hard (right hand panels) X-ray light curves of EI UMa, LS Peg and V426 Oph. We superimpose the confidence limits for power at each period bin being significant at the  $2\sigma$ ,  $3\sigma$  and  $4\sigma$  confidence intervals. The ‘tick’ mark in the top left panel represent the period at which a modulated signal has previously been reported (Table 2).

flow is more azimuthally symmetric and hence there is no modulation at the spin period and no precessing, tilted or warped accretion disc.

## 8 CONCLUSIONS

We have analysed the X-ray light curves of EI UMa, LS Peg and V426 Oph using a procedure which models the effect of red-noise in an appropriate manner. We have found evidence for peaks in the power spectra between  $\sim 100$ – $200$  sec which

are marginally above the  $3\sigma$  confidence level but only one peak above  $4\sigma$  (760 sec in the soft X-ray light curve of EI UMa). Apart from the latter peak, these periods have not been detected in previous observations of these sources, nor have we detected significant peaks in the power spectra at previously noted periods. We find no evidence for a modulation on the spin period in either LS Peg or V426 Oph, but confirm the result of a 760 sec period in EI UMa as reported by Baskill et al (2005) and Reimer et al (2008) which they believed is the signature of the spin period.

However, since all three systems show complex and high

absorption we believe that they are *bona fide* IPs. We speculate that we do not detect an X-ray modulation in LS Peg and V426 Oph at their spin period since the spin and magnetic axes of the accreting wide dwarf are closely aligned. V426 Oph and LS Peg show evidence for an orbital modulation in soft X-rays since material is lifted out of the orbital plane and crosses our line of sight to the accretion regions on the white dwarf.

Therefore, we speculate that there is a subset of IPs which are not expected to show a short period coherent modulation – previously taken to be a necessary characteristic of IPs. This will have implications for identifying objects as IPs and hence their space density. For instance, Barlow et al (2006) present a compilation of CVs detected using *Integral*/IBIS survey data. Out of the 9 CVs discovered as a result of *Integral* data, 4 have no detected period and are therefore regarded as ‘unclassified’ CVs. The fact that they are detected at hard X-rays (20–100keV) is consistent with them being IPs. We suggest that they are *bona fide* IPs which have closely aligned spin and magnetic axes and therefore do not show a coherent X-ray signal on their spin period.

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