Spin modulated X-ray emission from intermediate polars

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Summary. This paper describes a comparative study of all the intermediate
polars observed by EXOSAT. We present the X-ray pulse profiles of each
source and show that, in all cases, the modulation can be described in terms of
an increasing depth with decreasing energy. By considering the pulse phase-
resolved spectra, we show that the modulation cannot be due to simple phase
dependent absorption alone, but that models which combine photoelectric
absorption with an effect due to self occultation to produce the modulation can
explain the data. In addition, models using partial covering of the X-ray
emission region produce an improved fit to the overall dataset. To account
for the behaviour seen we present a picture of the accretion process using a
structured accretion flow and emission region. In this model the absorption and
occultation effects act in phase and both arise at the same pole of the white
dwarf. The typical sizes of the modulation due to occultation and absorption
both imply that the emission region must occupy, on average, at least one
quarter of the white dwarf’s surface.

1 Introduction

In common with other cataclysmic variables (CVs), intermediate polars are semi-detached,
interacting binaries containing a white dwarf accreting material from a red dwarf star which
fills its Roche lobe. There exists a sub-class of CVs in which the magnetic field of the white
dwarf is strong enough to influence the flow of material accreting on to it. These magnetic CVs
are usually subdivided into polars (or AM Her systems) and intermediate polars (or, probably
misleadingly, DQ Her systems) on the basis of the degree of synchronization between the
orbital period of the system and the spin period of the white dwarf. For a recent review of
magnetic CVs see Watson (1986).

Although the exact geometry of the X-ray emitting region in magnetic CVs is open to
question and may approximate to a cylindrical column (e.g. King & Shaviv 1984, hereafter
KS); an arc-shaped curtain (Rosen, Mason & Córdova 1988, hereafter RMC) or some other
arrangement (see Section 2), the basic idea behind the production of X-rays in these systems is
well understood (see, e.g. Frank, King & Raine 1985). As has been emphasized, the magnetic
field of the white dwarf is strong enough to control the accretion flow at some radius \( R_{\text{mag}} > R_{\text{wd}} \) from the white dwarf. Thus, within the radius \( R_{\text{mag}} \) the motion of the accreting material will be governed by the magnetic field lines, leading to radial infall of the accreting material on to a restricted region of the white dwarf surface in the vicinity of the magnetic pole. A stand off shock will form in the accretion flow close to the white dwarf and below this the plasma will settle on to a fraction of the surface \((f)\). The main cooling process operating below the shock is expected to be thermal bremsstrahlung radiation.

The purpose of the present analysis is to investigate the X-ray properties of all the known intermediate polars in a consistent and comprehensive manner, using data obtained with the EXOSAT Observatory for each source. Published results exist for much of the data considered here, however, these analyses have often been performed with different aims in mind and usually with a reference to the data of only one source. In the present work, we concentrate on the origin of the modulation of the X-ray flux at the spin period of the white dwarf. To address this we consider the pulse profiles and phase-resolved spectra of the sources and investigate how the data can be understood in terms of various models. In performing this analysis we assume that the intermediate polars form an homogenous set of objects. This may not be strictly true, but an ‘average’ pattern of behaviour may be determined.

2 Theoretical framework

In simple terms there are three possible causes of the X-ray modulation seen in magnetic CV systems. The modulation at the white dwarf spin period may be explained in terms of occultation of the X-ray emitting region by the body of the white dwarf itself; by phase-dependent photoelectric absorption in material in the line-of-sight or by an anisotropic emission process which directs the X-rays only into a region of restricted angular extent. Such a beaming model is analogous to the process believed to operate in radio and X-ray pulsars (see, e.g. White, Swank & Holt 1983). In general, if occultation is the cause then the modulation will not exhibit any variation as a function of energy, since it is a purely geometrical effect. If, on the other hand, photoelectric absorption is the cause then the pulse profiles will show an increase in modulation depth as the X-ray energy decreases.

A beaming model for magnetic CVs is considered by Imamura & Durisen (1983). Their results are only valid for the situation where the ratio of X-ray luminosity to the accreting fraction of the white dwarf is greater than about \( 5 \times 10^{35} \) erg s\(^{-1}\). This condition is only likely to be met (if at all) in the most luminous intermediate polar, namely GK Per in outburst, unless accreting fractions are extremely small \((f<0.001)\). Hence, we do not consider this model further.

In all other models, the magnetic axis is assumed to be offset from the spin axis of the white dwarf, so giving rise to pulsed X-ray emission as the white dwarf rotates. In the simplest models the emission region is envisaged as a filled cylinder with height, \( h \), much less than the radius of the white dwarf, \( R_{\text{wd}} \). Modifications to this simple geometry include: non-cylindrical emission regions, such as having the ‘footprint’ of the region as a ring or arc instead of a filled circle; tall emission regions with \( h \sim R_{\text{wd}} \) and multiple emission regions contributing to an overall structure. In the simple models any photoelectric absorption occurring in the source is assumed to be due to material with phase-dependent optical depth in the immediate vicinity of the emission region. Modifications to this model use several absorbing components with specific geometries.

There are two main models which have emerged in order to describe the intermediate polar phenomenon and which serve to demonstrate the types of geometry outlined above. These are the polecap and occultation model of KS (1984) and the accretion curtain and photoelectric absorption model of RMC (1988).
2.1 Polecap and Occultation Model

At the time of the work by KS, there was little evidence that the hard X-ray light curves of magnetic CVs showed any significant variation as a function of energy. They were prompted by the preponderance of sinusoidally modulated light curves amongst magnetic CVs to propose a model in which self occultation by the white dwarf was responsible for the modulation. In their model the accretion flow is funnelled on to the magnetic poles of the white dwarf and hard X-rays are emitted between the photosphere of the white dwarf and a shock at a height \( h \) (\( \ll R_{\text{wd}} \)) above it, so constraining a cylindrical emission region. Basing their arguments on statistical considerations of the shapes of the light curves they concluded that the polecap fraction, \( f \), in intermediate polars is likely to be of the order \( 2f \approx 0.5 \). KS further showed that the only opacity source in the emission region likely to be significant was electron scattering, and that the optical depth to infinity along the column was:

\[
\tau_{\text{es}}(\text{vert}) = 0.3 \dot{M}_{17} f \frac{1}{2} M_i^{-1/2} R_y^{-1/2}, \tag{1}
\]

whilst that across the column, parallel to the white dwarf surface, just above the shock was:

\[
\tau_{\text{es}}(\text{horiz}) = 0.1 \dot{M}_{17} f \frac{1}{2} M_i^{-1/2} R_y^{-1/2}, \tag{2}
\]

where \( \dot{M}_{17} \) is the mass accretion rate in \( 10^{17} \) g s\(^{-1} \), \( M_i \) is the white dwarf mass in \( M_\odot \) and \( R_y \) is its radius in \( 10^9 \) cm. Further, the material immediately above the shock should produce photoelectric absorption at a photon energy, \( E \):

\[
\tau_{\text{pe}} \approx 600 \tau_{\text{es}} E^{-3}. \tag{3}
\]

The strongly energy dependent modulation at low photon energies (\( E \lesssim 4 \) keV) predicted by this effect had not been observed then. (Although it has been since, as is shown in Section 4.) KS thus concluded that the conditions in magnetic CVs were such that the effects predicted by equations (1), (2) and (3) were small. Note also that, in their model, it is presumed that emission is seen from only one of the magnetic polar regions of the white dwarf otherwise the emission from the second pole would ‘cancel out’ the modulation due to the first. Thus, KS concluded that the observed X-ray intensity at any instant is proportional to the volume of that part of the (single visible) polecap which is not occulted by the body of the white dwarf.

2.2 Accretion Curtain and Photoelectric Absorption Model

RMC based their model on observations of EX Hya but suggested that it might be applicable to all intermediate polars. They argued that the footprint of the accretion flow is a small semicircle around the magnetic poles of the white dwarf, occupying a fractional area of only \( \sim 1\% \). Instead of a cylindrical column they proposed a tall, thin ‘curtain’ of material falling on to each magnetic pole of the white dwarf where the cross-section of the curtain at any height is in the form of an arc. The modulation in this model is caused by photoelectric absorption in the curtain. The minimum flux occurs when the accreting pole points towards the observer and one is viewing the emission region through the accretion flow. This is the opposite of the model of KS where minimum flux occurs when the polecap is pointing away from the observer. RMC argued that the effective accretion rate will vary along the arc of the accretion pattern, so giving varying temperature structure and shock height from one end of the curtain to the other. The shock height is smallest where the accretion rate is highest, at the sub-polar point. They further argued that the X-ray spectrum produced by such an emission region will appear as a continuous distribution of temperature components passing through a range of column densities. RMC concluded that the modulation seen in EX Hya is caused by photoelectric absorption and that this continuous distribution of temperature components and range of column...
densities can describe the modulation depths seen in the X-ray light curves of EX Hya. There is the possibility in this model that the second pole of such a system, below the disc plane, will contribute a modulation in phase with that of the first due to it being occulted by the body of the white dwarf [assuming that it is not blocked by the (inferred) accretion disc].

2.3 Overall Constraints

The pulse profiles of polars show a strong modulation which does not appear to vary as a function of energy. Two polars detected by the EXOSAT medium energy experiment are AM Her and EF Eri. Data on both of these sources were analysed during the course of this work and both are consistent with a constant modulation depth at energies between 2 and 10 keV. The modulation depth seen in AM Her is 76 ± 2 per cent whilst that in EF Eri is 70 ± 4 per cent. In intermediate polars, however, a strong energy dependence in the modulation depth is seen for most sources (Mason 1985; see also Section 4). This indicates that in polars geometrical effects are the most important and the modulation we see must be due to self occultation; whilst in intermediate polars photoelectric absorption must be of comparable importance.

3 The observations

The complete set of observations examined in the present work is listed in Table 1. The list includes all the sources observed by EXOSAT which were known to be (or suspected of being) intermediate polars or DQ Her stars. References to the previous publication of results from these data are included in Table 1. The data in each case consist of observations with the medium energy (ME) experiment and the low energy (LE) telescope on board EXOSAT (Turner, Smith & Zimmerman 1981 and de Korte et al. 1981). Of the sources, V533 Her, AE Aqr, V603 Aql and SW UMa were not significantly detected with the ME instrument; FO Aqr was not detected with the LE telescope and GK Per and V426 Oph were only marginally detected in the low energy band.

It is appropriate at this point to explain how the sources were selected for further analysis. V533 Her and AE Aqr are classified as DQ Her stars (along with the prototype itself). These three objects have spin periods less than 100 s, and of these only AE Aqr has in the past been detected at X-ray wavelengths (Patterson et al. 1980). The status of V603 Aql is uncertain. It had previously been detected as a hard X-ray source (Drechsel et al. 1983) but had obviously decreased in flux by the time of the EXOSAT observations. Similarly, the nature of SW UMa is in doubt since it was undetected as a hard X-ray source unlike all the other intermediate polars. V426 Oph presented a different problem. When the observation was analysed, the previously reported X-ray period of \( \sim 3600 \) s (Szkody 1986) was found not to be unique. Shorter periodicities were also evident but it was unclear whether the spin period of the white dwarf had been identified.

Hence, the observations which were analysed further were those of the eight sources: GK Per, V1223 Sgr, TV Col, AO Psc, EX Hya, FO Aqr, BG CMi and H0542 – 407. These sources all have much longer spin periods than the DQ Her stars and are all strong X-ray sources above 2 keV. In the remainder of this work, any reference to ‘the intermediate polars’ may be taken to mean these eight sources.

4 The light curves

For each observation of the intermediate polars listed in Table 1 background subtracted light curves were obtained in four energy bands: three from the ME (\( \sim 2-4, \sim 4-6 \) and \( \sim 6-10 \) keV)
Table 1. The observations.

<table>
<thead>
<tr>
<th>Source</th>
<th>Obs.</th>
<th>Date</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>GK Per</td>
<td>A</td>
<td>1983 Aug 9</td>
<td>[1],[2]</td>
</tr>
<tr>
<td>B</td>
<td>1983 Aug 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1983 Aug 24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1984 Sep 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>1985 Jan 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1984 Aug 29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1984 Sep 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TV Col</td>
<td>A</td>
<td>1983 Nov 26</td>
<td>[5],[6],[7]</td>
</tr>
<tr>
<td>B</td>
<td>1983 Nov 28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1985 Nov 17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FO Aqr</td>
<td>A</td>
<td>1983 Aug 10</td>
<td>[8],[9]</td>
</tr>
<tr>
<td>B</td>
<td>1983 Oct 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1985 Oct 22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BG CMi</td>
<td>A</td>
<td>1984 Jan 4</td>
<td>[10],[11]</td>
</tr>
<tr>
<td>B</td>
<td>1985 Apr 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AO Psc</td>
<td>A</td>
<td>1983 Sep 14</td>
<td>[12],[13]</td>
</tr>
<tr>
<td>B</td>
<td>1983 Sep 17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1985 Oct 23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1985 Oct 26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EX Hya</td>
<td>A</td>
<td>1983 July 30</td>
<td>[14],[15],[16],[17],[18]</td>
</tr>
<tr>
<td>H0542-407</td>
<td>A</td>
<td>1985 Feb 23</td>
<td>[19]</td>
</tr>
<tr>
<td>V426 Oph</td>
<td>A</td>
<td>1984 Sep 25</td>
<td>[20]</td>
</tr>
<tr>
<td>SW UMa</td>
<td>A</td>
<td>1985 Mar 17</td>
<td>[21]</td>
</tr>
<tr>
<td>AE Aqr</td>
<td>A</td>
<td>1984 July 8</td>
<td>[22]</td>
</tr>
<tr>
<td>V533 Her</td>
<td>A</td>
<td>1985 Apr 2</td>
<td>[23]</td>
</tr>
<tr>
<td>V603 Aql</td>
<td>A</td>
<td>1984 Sept 7</td>
<td>[24],[25]</td>
</tr>
<tr>
<td>B</td>
<td>1984 Sept 9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References to Table 1:

[22] Patterson, J. et al., 1980.

and one broad band from the LE telescope (\(\sim 0.05\)–2 keV). In the majority of these observations the LE telescope was used with the thin lexan filter in place. The only exception being observation A of EX Hya for which data obtained with the polypropylene filter has been considered instead. This filter has an almost identical energy response to the thin lexan filter, so the data can still be considered comparable with that obtained for other sources. Exceptions to this overall strategy were: observation E of EX Hya when the ME detectors were switched off for the entire observation; observation A of FO Aqr where it was not possible to produce
an adequate background subtracted light curve and observation E of GK Per, for which only data from the so-called 'normal' behaviour section of the observation has been used (see Norton, Watson & King 1988). Observations A, B and C of GK Per were obtained when this source was in optical and X-ray outburst whilst observations D and E were obtained during periods of quiescence. All other sources were observed at roughly the same X-ray flux for each observation.

The light curves which were obtained were all then folded at the respective spin periods of each source. The spin periods of all the intermediate polars were known prior to this work, either from X-ray or optical studies. Table 2 lists the spin periods along with a reference to a recently published determination of the period in each case. In all the data considered here, the modulation at the spin period is significant in at least some, if not all, of the energy ranges used. Examples of the folded light curves (repeated over two cycles for clarity and shifted so that pulse minimum appears at phase zero in each case) are shown in Fig. 1.

To characterize the overall modulation we measured the modulation depth of each source as a function of energy by finding the best fit sinusoid to each dataset. (A sine wave was chosen as the simple function which most closely approximated the shape of the observed modulation in the majority of cases.) The arbitrary phase zero points of the light curves for each observation were determined from the 2–4 keV data, and the depths in each of the other energy ranges were measured with respect to this. We define the modulation depth as the peak to peak sinusoidal amplitude divided by the maximum flux. The values obtained for each energy band of each observation are shown in Table 3 along with the 90 per cent confidence limits. As can readily be seen, all of the observations are consistent with a decreasing modulation depth with increasing energy. In many cases the modulation depths are subject to large errors, especially in the highest and lowest energy bands considered, due to the relatively low X-ray flux at these energies. As a result of these uncertainties some of the data (observations D and E of GK Per and observations A and B of TV Col) are also consistent with a constant modulation depth at all energies. It will be noticed that a few of the 90 per cent confidence limits shown for the modulation depths include values less than zero (e.g. most of the LE observations of V1223 Sgr, TV Col and BG CMi). This may indicate that a modulation 180° out of phase with that indicated is also a possibility within the constraints of the data.

5 The spectra

X-ray spectra from the ME instrument were obtained for each intermediate polar. The LE data, where available, provide a single point on the spectrum for each filter used in the instrument. The ME data provide the remainder of the spectrum with 36 pulse height channels covering the range 1–10 keV.

<table>
<thead>
<tr>
<th>Source</th>
<th>Spin Period (sec)</th>
<th>Reference to Period Determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1223 Sgr</td>
<td>745.43</td>
<td>Osborne, J. et al., 1985</td>
</tr>
<tr>
<td>TV Col</td>
<td>1911</td>
<td>Schrijver, J., Brinkman, A.C. &amp; van der Woerd, H., 1987</td>
</tr>
<tr>
<td>BG CMi</td>
<td>913.48</td>
<td>McHardy, I. et al., 1984</td>
</tr>
<tr>
<td>AO Psc</td>
<td>805.4</td>
<td>Warner, B. &amp; O’Donoghue, D., 1980</td>
</tr>
<tr>
<td>EX Hya</td>
<td>4021.61</td>
<td>Gilliland, R.L., 1982</td>
</tr>
<tr>
<td>H0542-407</td>
<td>1920</td>
<td>Tuohy, I. et al., 1986</td>
</tr>
</tbody>
</table>

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Figure 1. Examples of the pulse profiles in intermediate polars as a function of energy. The energy ranges in the four curves for each source are: 0.05–2.0, 2–4, 4–6 and 6–10 keV with energy increasing reading down the page. Note that GK Per and FO Aqr were not significantly detected in the lowest energy band so only three profiles are shown.
In this section we model the spectra in terms of a single source of X-rays. In the first models, the source is obscured by a simple absorber whilst in the second set it is obscured by a ‘patchy’ absorber (i.e. partial covering of the source). Within these two sets we first model the phase averaged spectra to determine the parameters which we assume to be phase independent. We then model the phase resolved spectra by allowing one or both of the normalization and intrinsic column density to vary as a function of spin phase. Thus the data and models which we fit to them are as follows:

(i) Phase averaged spectra: simple absorption.
(ii) Phase resolved spectra: simple absorption; varying $N_H$.
(iii) Phase resolved spectra: simple absorption; varying $N_H$; varying normalization.
(iv) Phase averaged spectra: partial covering.
(v) Phase resolved spectra: partial covering; varying $N_H$; varying normalization.

As a reference, Table 4 shows the $\chi^2$ values for all of the spectral fits performed. The following sections consider the five models above in order.

5.1 Model 1

First, the spectra taken as an average over all spin phase were considered. Models consisting of either a power-law or a thermal bremsstrahlung continuum, in each case with low energy absorption, were fitted to the spectra of each observation. In most cases the inclusion of an iron emission line was found to be justified in order to model the excess in flux above a simple continuum between 6 and 7 keV. The only observations not to show evidence for an iron line were observation E of GK Per, observation A of TV Col and the two observations of BG CMI.

If the models considered here are adequate fits to the data, there is a probability of ~85 per cent that any given $\chi^2$ will be less than ~1.3. We may therefore expect that ~85 per cent of the fits to a given model will have $\chi^2 < 1.3$ if the model adequately represents the whole dataset.
Table 3. Measured modulation depths.

<table>
<thead>
<tr>
<th>Source</th>
<th>Obs.</th>
<th>0.05 – 2.0 keV</th>
<th>2 – 4 keV</th>
<th>4 – 6 keV</th>
<th>6 – 10 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>GK Per</td>
<td>A</td>
<td>58 ± 2%</td>
<td>55 ± 1%</td>
<td>49 ± 1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>61 ± 3%</td>
<td>59 ± 1%</td>
<td>53 ± 1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>62 ± 1%</td>
<td>51 ± 1%</td>
<td>45 ± 1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>22 ± 6%</td>
<td>16 ± 7%</td>
<td>24 ± 9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>21 ± 8%</td>
<td>8 ± 14%</td>
<td>5 ± 29%</td>
<td></td>
</tr>
<tr>
<td>V1223 Sgr</td>
<td>A</td>
<td>37 ± 34%</td>
<td>29 ± 3%</td>
<td>21 ± 3%</td>
<td>7 ± 8%</td>
</tr>
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<td></td>
<td>B</td>
<td>44 ± 33%</td>
<td>30 ± 2%</td>
<td>16 ± 6%</td>
<td>12 ± 5%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>43 ± 58%</td>
<td>30 ± 4%</td>
<td>21 ± 8%</td>
<td>6 ± 14%</td>
</tr>
<tr>
<td>TV Col</td>
<td>A</td>
<td>42 ± 29%</td>
<td>26 ± 5%</td>
<td>24 ± 5%</td>
<td>16 ± 12%</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>20 ± 38%</td>
<td>35 ± 5%</td>
<td>13 ± 8%</td>
<td>19 ± 10%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>43 ± 46%</td>
<td>32 ± 3%</td>
<td>21 ± 3%</td>
<td>19 ± 8%</td>
</tr>
<tr>
<td>FO Aqr</td>
<td>B</td>
<td>90 ± 4%</td>
<td>60 ± 4%</td>
<td>33 ± 7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>78 ± 5%</td>
<td>51 ± 4%</td>
<td>36 ± 9%</td>
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</tr>
<tr>
<td>BG CMi</td>
<td>A</td>
<td>13 ± 99%</td>
<td>50 ± 10%</td>
<td>8 ± 15%</td>
<td>5 ± 27%</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>44 ± 23%</td>
<td>39 ± 7%</td>
<td>13 ± 11%</td>
<td>2 ± 38%</td>
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<tr>
<td>AO Psc</td>
<td>A</td>
<td>77 ± 21%</td>
<td>82 ± 2%</td>
<td>61 ± 3%</td>
<td>32 ± 8%</td>
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<td>76 ± 2%</td>
<td>61 ± 3%</td>
<td>53 ± 9%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>82 ± 23%</td>
<td>74 ± 2%</td>
<td>55 ± 3%</td>
<td>28 ± 8%</td>
</tr>
<tr>
<td>EX Hya</td>
<td>A</td>
<td>64 ± 4%</td>
<td>23 ± 1%</td>
<td>15 ± 2%</td>
<td>12 ± 6%</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>58 ± 4%</td>
<td>27 ± 2%</td>
<td>14 ± 4%</td>
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<tr>
<td></td>
<td>C</td>
<td>56 ± 4%</td>
<td>25 ± 2%</td>
<td>12 ± 3%</td>
<td>5 ± 10%</td>
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<td>57 ± 4%</td>
<td>28 ± 2%</td>
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</tr>
<tr>
<td>H0542-407</td>
<td>A</td>
<td>68 ± 9%</td>
<td>24 ± 7%</td>
<td>19 ± 12%</td>
<td>16 ± 10%</td>
</tr>
</tbody>
</table>

For this model, ~60 per cent of the phase averaged spectra have $\chi^2 > 1.3$. However, in many of these cases (e.g. FO Aqr and BG CMi), the data have very low signal-to-noise and the apparently acceptable fit is likely to be due to the poor quality of the data used. The only observations for which thermal bremsstrahlung continua were preferred over power laws, on the basis of the value for $\chi^2$, were those of V1223 Sgr. In all other cases the best-fit temperature in the thermal bremsstrahlung models were either high and poorly constrained (TV Col, GK Per observations D and E, AO Psc and H0542 – 407); unbounded (FO Aqr, BG CMi and GK Per, observations A, B and C) or the model was a particularly poor fit when compared with a power-law model (EX Hya).
Table 4. \( \chi^2 \) Values for the spectral fits.

<table>
<thead>
<tr>
<th>Source</th>
<th>Obs.</th>
<th>Model 1 (phase ave.)</th>
<th>Model 2 (pulse max./min.)</th>
<th>Model 3 (pulse max./min.)</th>
<th>Model 4 (phase ave.)</th>
<th>Model 5 (pulse max./min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GK Per</td>
<td>A</td>
<td>3.5</td>
<td>18/7.3</td>
<td>2.1/2.3</td>
<td>2.0</td>
<td>1.2/1.9</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.4</td>
<td>13/6.7</td>
<td>1.6/1.1</td>
<td>1.0</td>
<td>1.2/1.0</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>1.9</td>
<td>14/4.0</td>
<td>1.8/1.3</td>
<td>0.9</td>
<td>1.2/1.5</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>1.0</td>
<td>1.0/1.2</td>
<td>0.6/1.1</td>
<td>0.8</td>
<td>0.6/1.0</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>0.8</td>
<td>1.0/0.8</td>
<td>0.9/0.6</td>
<td>0.8</td>
<td>0.9/0.6</td>
</tr>
<tr>
<td>V1223 Sgr</td>
<td>A</td>
<td>2.4</td>
<td>2.3/1.6</td>
<td>1.6/1.7</td>
<td>1.1</td>
<td>1.4/0.7</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>2.1</td>
<td>1.6/2.7</td>
<td>1.4/2.5</td>
<td>1.7</td>
<td>1.3/2.0</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2.5</td>
<td>1.9/1.6</td>
<td>1.7/1.5</td>
<td>1.7</td>
<td>1.2/1.2</td>
</tr>
<tr>
<td>TV Col</td>
<td>A</td>
<td>0.7</td>
<td>0.8/0.8</td>
<td>0.7/0.7</td>
<td>0.7</td>
<td>0.7/0.7</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.1</td>
<td>1.0/1.1</td>
<td>0.9/1.2</td>
<td>1.0</td>
<td>0.8/1.0</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>4.1</td>
<td>5.8/5.3</td>
<td>5.5/4.9</td>
<td>1.1</td>
<td>1.5/1.2</td>
</tr>
<tr>
<td>FO Aqr</td>
<td>B</td>
<td>0.7</td>
<td>1.3/0.7</td>
<td>0.7/0.7</td>
<td>0.6</td>
<td>0.7/0.9</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.8</td>
<td>0.5/0.9</td>
<td>0.6/1.0</td>
<td>0.7</td>
<td>0.5/0.9</td>
</tr>
<tr>
<td>BG CMi</td>
<td>A</td>
<td>0.6</td>
<td>1.0/0.4</td>
<td>0.9/0.4</td>
<td>0.6</td>
<td>0.9/0.5</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.6</td>
<td>0.7/0.6</td>
<td>0.7/0.6</td>
<td>0.6</td>
<td>0.7/0.6</td>
</tr>
<tr>
<td>AO Psc</td>
<td>A</td>
<td>0.8</td>
<td>4.7/2.3</td>
<td>0.9/1.2</td>
<td>0.7</td>
<td>0.8/1.3</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.9</td>
<td>3.0/1.6</td>
<td>0.8/1.2</td>
<td>0.8</td>
<td>0.9/1.3</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>3.7</td>
<td>15/3.7</td>
<td>3.3/1.3</td>
<td>1.6</td>
<td>1.6/1.0</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>2.2</td>
<td>12/2.4</td>
<td>2.4/1.3</td>
<td>1.3</td>
<td>1.1/1.3</td>
</tr>
<tr>
<td>EX Hya</td>
<td>A</td>
<td>1.3</td>
<td>4.4/1.8</td>
<td>1.2/0.9</td>
<td>1.2</td>
<td>1.7/3.7</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.2</td>
<td>3.4/5.5</td>
<td>2.9/1.2</td>
<td>1.2</td>
<td>1.5/1.3</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>3.1</td>
<td>7.6/8.0</td>
<td>2.0/4.1</td>
<td>2.0</td>
<td>2.2/2.6</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>1.0</td>
<td>4.7/6.9</td>
<td>0.8/1.4</td>
<td>0.9</td>
<td>0.9/1.2</td>
</tr>
<tr>
<td>H0542-407</td>
<td>A</td>
<td>1.0</td>
<td>1.1/1.4</td>
<td>0.7/1.2</td>
<td>1.1</td>
<td>0.7/1.1</td>
</tr>
</tbody>
</table>

It should be noted that the data which showed unacceptable fits to the simple power-law model have high signal-to-noise and their spectra show evidence for an excess flux above the simple model at low energies. Two other points to notice are that iron lines are present in most of the spectra and that power-law continua are preferred to thermal bremsstrahlung continua in many cases.

Simple theory predicts that the dominant emission process in these systems will be optically thin bremsstrahlung at characteristic temperatures \( kT \sim 30 \text{ keV} \), for a solar mass white dwarf (e.g. Frank, King & Raine 1985). The fact that power-law continua produce fits which are better constrained may indicate that the emission arises in several regions with different temperatures superimposed. Over the limited spectra region considered (\( \sim 1-10 \text{ keV} \)), a power law will often give a better approximation to such an integrated spectrum than a single bremsstrahlung continuum. Also, we do not detect most sources above \( \sim 10 \text{ keV} \) and this makes it difficult to accurately constrain bremsstrahlung continua with temperatures much higher than this. This too is probably responsible, at least in part, for the poor fits to the data with thermal bremsstrahlung continua.

5.2 Model 2

To investigate spectral changes associated with the modulation seen at the spin period of the white dwarf, pulse phase spectroscopy was performed. Due to the low signal-to-noise apparent in many observations, it was only possible to determine the spectra as a function of phase by
dividing the data into two bands: the pulse maximum and the pulse minimum. In this model, the purpose of the analysis was to see if a change in the absorbing column as a function of phase could adequately explain the spectra observed. Therefore only a single model continuum was used: a thermal bremsstrahlung in the case of V1223 Sgr and a power law in all other cases. For these fits the photon index (or bremsstrahlung temperature), normalization and emission line energies where needed were maintained at the value found for the phase-averaged spectrum. Hence, only the column density and the emission line strengths where needed, were allowed to vary. The latter was because, if the emission line is due to fluorescence, its strength is likely to change as the column density in the line-of-sight changes.

The fits to the phase-resolved spectra with a single free parameter (plus the iron line strength) do not give as good a result as the fits to the phase-averaged data (only ~ 35 per cent show a $\chi^2 < 1.3$, see Table 4). This indicates that the simple model used here, where a single absorbing column varies as a function of phase, is not a good representation of all the observations. However, all the observations do show an increase in absorbing column at pulse minimum over that which is seen at pulse maximum. This is a good indication that varying photoelectric absorption is, at least in part, responsible for the modulation seen. The main failure of this model, with respect to the phase-resolved spectra, is that often a change in the continuum normalization is indicated by an examination of the residuals to the fit. At the higher energies, which are relatively unaffected by photoelectric absorption, the continuum appears above the fitted model at pulse maximum and below it at pulse minimum.

The energy of the emission line (within 90 per cent error limits) in each case is consistent with a value of 6.4–6.5 keV. Hence it is possible that the observed lines are due to fluorescent iron K-line emission from low ionization (Fe x–xix), cool ($T < 10^5$ K) iron ions (Makishima 1986). The mean equivalent width of the lines is 0.46 keV at pulse maximum and 0.67 keV at pulse minimum. This is consistent with the idea of a fluorescent origin. However, the range of equivalent widths is ~ 0.2–1.0 keV and for column densities of the magnitude seen we would only expect equivalent widths of the order ~ 0.01–0.1 keV (Makishima 1986). The discrepancy may be due to the difficulty in accurately measuring the equivalent widths of the lines or may indicate an enhanced iron abundance in the absorbing medium.

5.3 Model 3

The deficiencies of the second model prompted the following model in which, in addition to allowing the column density to vary, the normalization was also made a free parameter in the fits to the phase resolved spectra. Once again, the continuum shape and iron line energy were maintained at the values found for the phase averaged case.

For this model, ~ 65 per cent of the fits have $\chi^2 < 1.3$ and ~ 60 per cent of the observations show a statistically improved $\chi^2$ over the previous model. However, the observations with the highest signal-to-noise are poorly fit and still exhibit an excess flux at low energies above that predicted by the simple absorber model. Nevertheless, in all of the observations, the pulse maximum spectra are characterized by a higher normalization constant and a lower column density than the pulse minimum spectra. (Except for BG CMi where the normalization constants show the reverse of the general trend, albeit with overlapping errors.)

5.4 Model 4

To model the low energy excess flux which is apparent in the sources with the highest signal-to-noise, we introduce the idea of partial covering. A partially covered source will allow a fraction of the emission to escape and this will appear in the spectrum as an ‘extra’ low energy compo-
nent. Such an effect may also be produced by a genuine second source of (low energy) X-rays; however, we choose to model the spectrum in the way stated since it can be related directly to the probable form of the accretion flow as discussed in Section 6.

We assume a fraction $X_1$ of the source is seen through a column density $N_{\text{H}_1}$, and the remainder of the source, a fraction $X_2$ such that $X_1 + X_2 = 1$, is seen through a column density $N_{\text{H}_2}$. We refer to $X_1$ as the uncovered fraction of the source, hence $N_{\text{H}_1}$ can be thought of as the ‘interstellar’ column density. $X_2$ is the covered fraction of the source and $N_{\text{H}_2}$ can be thought of as being the sum of two components: the ‘intrinsic’ column density plus the ‘interstellar’ column density. Power-law fits to the phase-averaged data were performed with all parameters free except for the emission line energy determined in model 1. (It was decided to fix this value in order to reduce the number of free parameters in the model.) A model with a thermal bremsstrahlung continuum did not provide an improved fit to any of the spectra.

The results in Table 4 show $\sim 80$ per cent of the phase-averaged spectra have $\chi^2 < 1.3$ for this model. In many cases the spectral parameters are rather poorly constrained, indicating that the spectra may be over-parameterized for the quality of the data available. However, the introduction of partial covering is able to fit the low energy excesses seen with previous models in the high signal-to-noise data. Example spectra are shown in Fig. 2 with the best fit model for this phase-averaged case. The ratio $X_1/X_2$ was used as a model parameter in the fits. Values obtained for this in the various sources were typically less than one, indicating that the majority of the source is covered in each case.

5.5 Model 5

Keeping the photon index, line energy, covered fraction and ‘interstellar’ column fixed at the values found for the phase-averaged spectra (model 4), the remaining model parameters (the ‘intrinsic’ column and normalization, plus the iron line strength where necessary) were determined for the pulse maximum and pulse minimum spectra. In this case, we again see $\sim 80$ per cent of the observations with $\chi^2 < 1.3$ (Table 4). This is therefore an improvement over model 3 (which had similar variable parameters but a simple absorber). The individual cases where the improvement is statistically significant are the observations with the highest signal-to-noise ratio.

Fig. 3 shows how the column density and normalization vary between the fits to the spectra in the two different states for this model. In all observations (except for GK Per observations D and V1223 Sgr observations A and C, where substantial uncertainty exists in the best-fit values) we see an increase in absorbing column density in going from pulse maximum to pulse minimum. We also see a decrease in the normalization constant in all cases (except for BG CMi and V1223 Sgr observation B, where the uncertainties in the best fit values do not rule this out). A further point to notice from these fits is the fact that even during pulse maximum, the ‘intrinsic’ column density is quite large ($\sim$ a few $\times 10^{22}$ cm$^{-2}$) in most cases, thus indicating a large amount of absorbing material present in the system which is visible at all phases.

5.6 Interpreting the Models

A varying photo-electric absorption and normalization, with a single component continuum, is thus one way of modelling the phase resolved spectra of intermediate polars. The higher signal-to-noise data also require a partially covered source of X-rays instead of a simple absorber.

We now use the parameters found from the spectral fits to derive predicted modulation depths. These are used to justify the comments made above regarding the most suitable
Figure 2. Examples of the X-ray spectra of intermediate polars. The data and best-fit are shown for model 4. Diamonds represent LE data points and crosses the ME data points.
Figure 3. The measured variation in $N_H$ and normalization as a function of phase in model 5. Open circles represent the values at pulse maximum, filled circles represent the values at pulse minimum. The error bars are the 90 per cent confidence limits in each case.

spectral models for intermediate polars. If we assume that the varying column density as a function of spin phase represents a real change in the intrinsic line-of-sight absorption, then the modulation depth produced by such a change is:

$$\Delta_{\text{abs}(\text{sim})} = 1 - \exp(\tau_H - \tau_L)$$

in the case of the simple absorber and:

$$\Delta_{\text{abs}(\text{par})} = \frac{1 - \exp(\tau_H - \tau_L)}{1 + (X_1/X_2) \exp(\tau_H - \tau_I)}$$

in the case of the partial absorber, where $\tau_H$ is the optical depth at pulse maximum due to the intrinsic column plus the interstellar column; $\tau_L$ is the optical depth at pulse minimum due to the intrinsic column plus the interstellar column and $\tau_I$ is the optical depth due to the interstellar column alone. Relations between the optical depth and equivalent hydrogen column density as a function of energy may be found in Zombeck (1980). Plots of modulation depth versus energy for a range of intrinsic absorbing columns, calculated using equations (4) and (5), are shown in Fig. 4. It should be noted that the absorbing columns shown in the figures are the change in intrinsic column needed to produce a modulation of the given depth not the total absorbing column measured in the spectrum of a source at any instant. In the case of the partial...
covering model, the covered fraction and interstellar column are set at typical values to produce the plot shown. A comparison between the two sections of Fig. 4 illustrates the effect of the diluting component which arises as a result of the partial covering.

We may also assume that the varying normalization in the phase resolved spectral fits represents the effect of self occultation on the X-ray emission region. Hence the modulation depth due to this effect may be calculated as:

\[ \Delta_{\text{occ}} = \frac{A_H - A_L}{A_H} \]  

(6)
where $A_{\text{H}}$ is the normalization constant found in the fit to the pulse maximum spectrum and $A_{\text{L}}$ is the normalization constant found in the fit to the pulse minimum spectrum. If we assume that the two modulation effects, $\Delta_{\text{abs}}$ and $\Delta_{\text{occ}}$, act in phase with each other the overall predicted modulation depth, $\Delta_{\text{pred}}$, is given by:

$$
\Delta_{\text{pred}} = (\Delta_{\text{abs}} + \Delta_{\text{occ}}) - (\Delta_{\text{abs}} \times \Delta_{\text{occ}}).
$$

(7)

So, for the three spectral models used to fit the phase resolved spectra (models 2, 3 and 5) the predicted modulation depth as a function of energy may be calculated. Model 2 thus represents a simply covered source undergoing phase dependent photoelectric absorption only; model 3 represents a simply covered source undergoing both phase dependent photoelectric absorption and self-occultation and model 5 represents a partially covered source also undergoing both types of modulation. Values for the predicted modulation depth were calculated in each of the four energy bands used in the analysis of the folded light curves (Section 4), with due allowance being made for the detector response functions and the shapes of the observed continua.

To examine the effectiveness of these models, a comparison may be made between the measured and predicted modulation depths. However, to perform this comparison it is first necessary to reconsider the way in which the modulation depths were measured directly from the light curves. The pulse phase spectroscopy was performed in two phase bands only, so to consider the modulation depths in the same way we fit the folded light curves with a square wave and use the parameters from these fits to calculate revised modulation depths. It should be noted that we do not intend to imply by this analysis that the pulse profiles can be accurately modelled as a square wave modulation, it is simply a necessary procedure to compare the data in the form of folded light curves with the data in the form of (two-state) phase-resolved spectra.

Fig. 5 shows the average residuals calculated as the difference between the predicted depths and the measured (square-wave) depths, as a function of energy. These residuals are the mean over all 24 observations and are shown along with the mean (90 per cent confidence) error for the three models discussed above. The mean residuals from models 3 and 5 are less than those from model 2 at each energy. This illustrates that a combination of the two modulation effects describes the data better than photoelectric absorption alone. Models 3 and 5 have similar residuals in the three highest energy bands but in the lowest band model 5 shows an improvement. This illustrates the effect of the partial covering. We emphasize that we are treating the intermediate polars as an homogenous set of objects, so we are interested in the average behaviour of the sources when considered in the light of each model. We clearly cannot be totally confident that this approach is correct, but it is a useful assumption.

The modulation depths in the case of spectral model 2 may be described by two free parameters (the two column densities); in spectral model 3 by four free parameters (two column densities and two normalizations) and in spectral model 5 by six free parameters (three column densities, two normalizations and the ratio of covered to uncovered fractions). Thus, to characterize the ability of the three models to predict the modulation depths we compare the 90 measured depths (Table 3) with the corresponding predictions of each model. This gives $\chi^2 = 32$ (88 d.o.f.) for spectral model 2, $\chi^2 = 2.0$ (86 d.o.f.) for spectral model 3 and $\chi^2 = 1.0$ (84 d.o.f.) for spectral model 5.

This confirms the comments made above that a combination of photoelectric absorption and self occultation can describe the phase-resolved spectra in intermediate polars (models 3 and 5). There is also reason to believe that a single partially covered source of X-rays is a better representation of the emission than a simple homogenously covered source. However, we note that the partial covering is probably not a unique description of the data. Models containing two or more sources of X-rays are likely to adequately fit the spectra also.
Figure 5. The residuals (predicted depth – measured depth) as a function of energy for models 2, 3 and 5. Values shown represent the mean residuals over all 24 observations and error bars show the mean 90 per cent confidence limits. The three models are offset slightly in the energy axis for clarity.

6 The accretion flow

We are now in a position to describe a model for the accretion flow processes which can explain the behaviour of the light curves and phase-resolved spectra in intermediate polars. It should be emphasized that the approach we have taken was simply to see what the data (the folded light curves in different energy ranges and the spectra resolved as a function of phase) indicated regarding the accretion processes taking place. We have arrived at a model containing two components of modulation as described above, using a single source of X-ray emission. Further points arising from the analysis are that iron emission lines are present in nearly all the sources; that power-law continua are usually preferred over thermal bremsstrahlung continua and that high intrinsic column densities are present at all phases in most sources.

The first possibilities for physical models of the cause of the modulation are those described in Section 2. The KS model fails because it cannot reproduce a varying modulation depth with energy. Any model relying solely on photoelectric absorption of a single source of X-rays (however covered) also fails because it cannot explain the large modulation depths which are seen at high energies in many of the sources. Fig. 3 shows that, in general, the spectra indicate a change in $N_H$ with phase of $\approx 5 \times 10^{22}$ atoms cm$^{-2}$. Fig. 4 shows that this will give rise to an absorption modulation depth of less than $\sim 5$ per cent at energies above 6 keV, whereas typical depths seen in the light curves (Table 3) are greater than $\sim 15$ per cent. A model such as that of RMC could produce high modulation depths due to photoelectric absorption, but RMC do not suggest that their model can do this. High modulation depths at high energies are not a natural feature of their model. The RMC model also includes the possibility of occultation combining with photoelectric absorption, as is apparent here from a consideration of a complete set of observations. In their model the occultation arises by allowing a contribution from the second pole (below the orbital plane). We prefer to investigate another possible model where the absorption and occultation effects act in phase and arise at the same pole of the white dwarf. We note that EX Hya is probably the source which is least well fit by the spectral model
we adopt. Since we are treating the intermediate polars as an homogenous set we make no special case for this source, but it may well be that it has a different status and is more correctly described by the RMC model.

To derive a model based on the results presented here, we follow the discussion of Hameury, King and Lasota (1986, hereafter HKL). They argue that accretion discs do not form in these systems, unless the orbital period is greater than \( \sim 5 \) hr. The value of 5 hr is uncertain since it relies on assuming a value for the magnetic moment of these systems, which may vary from source to source. Hence we assume that accretion discs do not exist in any of the intermediate polars. The possible exception to this is GK Per which has an orbital period of \( \sim 48 \) hr. However, this is also one of the few sources for which there is no evidence for the presence of an accretion disc. In this model we require that there is little or no contribution from the pole below the orbital plane. With no accretion disc present to hide the second pole, this will arise if the accretion occurs mainly on to just one of the magnetic poles as a result of the field pattern being asymmetric with respect to the white dwarf, and hence the orbital plane (HKL). The profiles of the X-ray light curves of intermediate polars (Fig. 1) suggest that they do not contain two opposed poles with similar emission properties, unless absorption dominates the light curve formation as in the model of RMC. It may be the case that those intermediate polars with two-pole emission are not detected, since their light curves are essentially unmodulated and thus selected against. Perhaps we only detect intermediate polars which have a severe magnetic field asymmetry.

Following HKL, we assume that the accretion stream from the secondary star impacts the magnetosphere of the white dwarf at a radius, \( R_{\text{mag}} \). This is the point where the magnetic effects are able to overcome the ram pressure of the stream material and a shock forms. The effect is envisaged as a 'splash' and may be visualized as similar to the jet from a hose pipe directed on to a rotating sphere. This may explain the large column densities seen at all spin phases in most of the sources. However, it is not clear that such a splash could distribute material all around the white dwarf so that the column density would be independent of orbital phase. After the shock at \( R_{\text{mag}} \), the material carries on in the form of cool, optically thick blobs which, initially, are not threaded by the magnetic field. Kelvin–Helmholtz instabilities will proceed to strip material from the surface of the blobs and the small droplets thus formed will be constrained to follow the magnetic field lines. HKL show that, depending on the efficiency of the Kelvin–Helmholtz instability process, by the time the blobs have reached some radius \( r \sim R_{\text{mag}}/2 \) they can either be completely disrupted into small droplets and thus constrained to follow the field lines towards the magnetic pole or still be substantially intact and thus follow ballistic trajectories which result in their impact with the white dwarf over a larger area. It is most likely that the flow will be composed of a combination of these two structures.

The large blobs in the accretion flow approaching the white dwarf will give rise to considerable structure in the polecap region. Each blob is likely to form its own 'accretion tube' with many tubes of varying shock height comprising the overall accretion polecap. Between these postulated accretion tubes there may exist a wind driven off the surface of the white dwarf. This mechanism was described by Watson, King & Williams (1987) to account for the flickering observed in the X-ray light curve of the polar source EF Eri. Similar flickering is observed in intermediate polars, a discussion of which we reserve for a future paper. The droplet component of the accretion flow will create a more evenly distributed accretion region around the individual accretion tubes. Thus the region of X-ray emission will be highly structured, and a partially covered or patchy absorber is a natural description of such a source. We thus associate the photoelectric absorption component with material in the immediate vicinity of the emission region.

The problem of whether the modulation due to occultation is in phase with that due to photoelectric absorption depends on the relative optical depths to the source as the white
dwarf rotates. To estimate how the optical depth varies in viewing the emission region from the side (across the polecap region) and from above (down on to the polecap region), we consider equations (1), (2) and (3) from earlier. This is a simple approach to the problem but within this framework, the necessary condition that the modulation due to absorption be in phase with that due to occultation is that:

\[ \tau(\text{vert}) < \tau(\text{horiz}). \] (8)

Considering the accretion tubes arising from the large blobs, in equations (1) and (2), \( f_{-2} \) is now the fractional area of each of these. If we assume that the blobs are not sparsely distributed, and hence there are sufficient accretion tubes for any line-of-sight to pass through several of them, we must scale the value of \( \tau(\text{horiz}) \) by a factor which is the square-root of the number of tubes within the nominal area of the overall polecap region. If the footprint area of each tube is \( f_{-2} \) and that of the whole accreting polecap is \( F_{-2} \), then the number of accretion is \( F_{-2}/f_{-2} \). So using this factor and equations (1), (2) and (3), equation (8) becomes simply:

\[ F_{-2}^{1/2} > 3, \] (9)

independent of \( f_{-2}, M_{17}, R_9 \) and \( M_1 \). Equation (9) is just what would result from considering a single homogenous polecap such as that produced by an even distribution of droplets. So, in this simple scenario, an overall accreting fraction occupying greater than \( \sim 9 \) per cent of the white dwarf surface is sufficient to ensure that the modulation due to photoelectric absorption is in phase with that due to occultation.

This model may also explain the fact that power-law continua are preferred when fitting the spectra. The individual ‘tubes’ of accretion will be independent sources of bremsstrahlung radiation at differing temperatures depending on the conditions existing in any one tube. Hence, a power-law continuum will be a better representation of such a combination of emission processes than a single bremsstrahlung continuum alone.

7 Discussion

7.1 The size of the emission region

The model for the accretion flow must be able to accommodate both the size of the modulation produced by occultation and the size of the column densities required by the absorption modulation. These two facts are considered below.

Values for the occultation modulation depth calculated using equation (6) are typically between 15 and 35 per cent, the average value being \( \sim 24 \) per cent. This is a relatively small effect and intuitively implies that one dimension of the emission region must be relatively large. KS show that in the simplest case, the shape of the occultation modulation depends on just three parameters: the polecap fractional area, \( f \); the magnetic co-latitude, \( m \); and the line-of-sight inclination angle, \( i \) (assuming \( h < R_{wd} \)). KS further compute the probabilities, as a function of \( f \), of finding a source showing one of three forms of behaviour: no modulation; a total eclipse (100 per cent modulation); and a sinusoidal or flat-topped modulation. We ignore the sources with no occultation modulation since these may not show much absorption dependent modulation either and so would not be detected as intermediate polars. Of the eight sources we analyse, all have occultation modulation depths of less than 100 per cent. Therefore the probability of finding a modulation of this form is likely to be greater than eight times the probability of finding a source showing 100 per cent modulation. Using the results of KS this gives:

\[ \sin \beta > 4 \left( \frac{\pi}{2} - \beta \right) \cos \beta \] (10)
where $\beta$ is the angle subtended by the polecap region such that: $\cos \beta = 1 - 2f$. This implies $f > 0.27$. Further, this is very much a lower limit to $f$, since the occultation modulation seen is obviously much less than 100 per cent in each case.

There are several possible adjustments to this simple picture. First, the emission region may have significant vertical extent and so the occultation produced by a given combination of angles would be smaller. Also, selection effects may in some way determine that we only see systems within a small range of $i$ and $m$ values. Finally, the second pole of these systems may contribute a modulated flux, out of phase with that from the first pole. However, as long as the emission areas at the two poles are not identical, due to an asymmetrical field pattern as mentioned above, some residual modulated flux will remain.

Within the model described in Section 6, the change in absorbing column between pulse maximum and pulse minimum can be estimated as due to the change in optical depth: $\tau(\text{horiz}) - \tau(\text{vert})$. As mentioned in that section, when considering the individual accretion tubes, $\tau(\text{horiz})$ has to be scaled by a factor which takes into account the many tubes making up the polecap. Similarly, when calculating absolute values for the column densities, the accretion rate per tube (as $\dot{M}$ in equations (1) and (2) now becomes) can be replaced by the total accretion rate divided by the number of accretion tubes (assuming that all the accretion takes place by this mechanism). These scalings have the net effect of leaving equations (1) and (2) unchanged, except that they now apply to a collection of accretion tubes making up a single polecap. So, using equations (1), (2) and (3) we see that, for an emission region occupying $\sim 27$ per cent of the white dwarf surface (as indicated above), the change in column density between pulse maximum and pulse minimum is $\sim 3 \times 10^{22}$ atoms cm$^{-2}$ (assuming $\dot{M}_{17}$, $M_1$ and $R_0$ are all $\sim 1$). Further, the absolute values of the column density in looking down on to and across the emission region are $\sim 4 \times 10^{22}$ and $\sim 7 \times 10^{22}$ atoms cm$^{-2}$ respectively. These figures are of the same order as the column densities actually measured in the sources at pulse maximum and pulse minimum (e.g. see Fig. 5).

Hence, both the occultation modulation and the photoelectric absorption modulation can be understood in terms of a large emission area.

### 7.2 A COMPARISON WITH POLARS

The main differences between the light curves and spectra of polars and intermediate polars are as follows:

(i) The light curves of polars show roughly constant modulation depth with X-ray energy whilst intermediate polars show an increasing depth with decreasing energy. Also the depths are generally higher (up to $\sim 100$ per cent) in polars.

(ii) The X-ray spectra of polars typically show a lower column density than intermediate polars and often exhibit an ultra-soft component.

Owing to their shorter orbital periods, the accretion rates in polars are predicted to be lower than those in intermediate polars (e.g. HKL). Also the influence of the white dwarf’s magnetic field is probably much stronger, since the magnetospheric radius in polars is comparable with the orbital separation. Hence the accretion flow itself may be much less disrupted than in intermediate polars with a much weaker shock at the magnetospheric boundary. In the light of the scenario presented in Section 6, these ideas provide an explanation for the two effects listed above. With a more orderly accretion flow and a ($\sim 10$ times) smaller accretion rate, the contribution of photoelectric absorption to the modulation is likely to be less. This would enhance the contribution of occultation, and thus lead to approximately constant modulation depths at all energies. Further, a more orderly flow may give rise to a smaller accreting area.
This in turn would lead to more strongly modulated light curves as a result of self occultation. The lower photoelectric absorption would also enable the emergence of the ultra-soft spectral component from the photosphere of the white dwarf.

8 Conclusions

We have shown that light curves of intermediate polars folded at the spin period of the white dwarf are all consistent with an increasing modulation depth as energy decreases. We take this as being a strong indication that photoelectric absorption is, at least in part, responsible for the modulation. The phase resolved spectra are consistent with the column density increasing and the normalization decreasing in moving from pulse maximum to pulse minimum. We interpret these changes as indicating that the modulation is composed of two components: one due to photoelectric absorption and one due to self occultation. In order to adequately describe their spectra, the observations with the highest signal-to-noise also require an effect such as that produced by a partially covered source. The parameters determined from the spectral fits enabled predictions of the modulation depths for each source to be made. These were found to be in accord with the measured depths, thus confirming the choice of the spectral model as a valid description of the data. The model used can be understood in terms of a structured emission region in the vicinity of the white dwarf. An accretion flow as suggested by Hameury, King & Lasota (1986) can explain the features observed. The average modulation depth due to occultation is \( \sim 24 \) per cent and the modulation depth due to photoelectric absorption can be explained by the column density changing by a few \( \times 10^{22} \) atoms \( \text{cm}^{-2} \) between pulse maximum and pulse minimum. These facts can be understood in terms of large emission regions occupying greater than one quarter of the white dwarf’s surface. Large emission areas are predicted by Chanmugam & Frank (1987) in order to explain the lack of optical polarization from intermediate polars.

A test for the model presented here would be to obtain high signal-to-noise spectra and pulse profiles of intermediate polars out to higher energies. The model predicts that the modulation depth of the pulse should be roughly constant (the depth due to occultation only) at energies greater than about 10 keV and that spectra resolved more closely in phase should show gradual changes in normalization and intrinsic column density with the modulation.

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