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The energy balance of polars revisited

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ABSTRACT

In the *EXOSAT* and *ROSAT* eras a significant number of polars were found to show a soft/hard X-ray ratio much greater than that expected from the standard accretion shock model. This was known as the 'soft X-ray excess'. We have made an snapshot survey of polars using *XMM-Newton* and determined their soft/hard ratios. We find that less than one in five of systems show a significant soft X-ray excess, while the rest show ratios consistent with that predicted by the standard model. We have investigated the discrepancy between this and the previous investigations by re-examining all the available *ROSAT* PSPC pointed observations of polars using more recent calibrations than in the original studies. We find that these data show an energy balance ratio which is broadly consistent with that of our *XMM-Newton* results. We conclude that the previous studies were affected by the data being less well calibrated. We discuss which physical mechanisms might give rise to a high soft X-ray excess and whether systems with high ratios show more variation in soft X-rays. Surprisingly, we find that 6 out of 21 systems found in a high accretion state did not show a distinct soft X-ray component. Two systems showed one pole with such a component and one which did not. Based on the ratio of the observed soft X-ray to UV flux measurements (which were obtained simultaneously using the Optical Monitor) we suggest that this is because the reprocessed component in these systems is cool enough to have moved out of the soft X-ray band and into the EUV or UV band.

Key words:
Physical Data and Process: accretion – Stars: binaries – Stars: cataclysmic variables – X-rays: binaries

1 INTRODUCTION

Polars or AM Her systems are accreting binary systems in which material transfers from a dwarf secondary star onto a magnetic ($B \sim$10–200MG) white dwarf through Roche lobe overflow. For polars in a high accretion state, the accretion flow generally forms a strong shock at some height above the photosphere of the white dwarf. The maximum temperature in the post-shock flow is set by the mass of the white dwarf. For a $0.7M_{\odot}$white dwarf the shock temperature is $\sim$30keV, with the temperature decreasing as the gas settles onto the white dwarf. Some fraction of the hard X-rays intercept the photosphere of the white dwarf, are thermalised and then re-radiated as soft X-rays or in the extreme UV. The standard model of the shock region predicts the ratio of this reprocessed radiation to that directly emitted by the shock, $L_{reprocessed}/L_{shock} \sim 0.5$ (eg Lamb & Masters 1979, King & Lasota 1979). For a recent review of the physical processes occurring in the shock region see Wu (2000).

Observations made using *EXOSAT* (1983–1986) found that a number of polars showed a large 'soft X-ray excess': if the reprocessed component was emitted as soft X-rays, the ratio, $L_{reprocessed}/L_{shock}$, was well in excess of that predicted by the standard model. In the following decade, Ramsay et al (1994) and Beuermann & Burwitz (1995) found using *ROSAT* (1990–1999) data that many systems showed large excesses. Beuermann & Burwitz (1995) calculated the ratio in the *ROSAT* band (0.1-2.4keV). These authors suggested that for systems with magnetic field strengths $\gtrsim$30MG, cyclotron radiation dominates the emission from the shock (Lamb & Masters 1979): if this was taken into account then the excess would largely disappear. On the other hand, Ramsay et al (1994), found that when bolometric luminosities were used, a significant number of systems nevertheless showed large soft X-ray excesses.

Various models have been put forward to account for the soft X-ray excess. These include nuclear burning on the surface of the white dwarf (Raymond et al 1979, Papaloizou, Pringle & MacDonald 1982), accretion energy being transported by electron conduction into the white dwarf and being re-emitted as soft X-rays (Fabian, Pringle & Rees 1976, King & Lasota 1980, Frank, King & Lasota 1988) and the bombardment model (Kuijpers & Pringle 1982, Thompson & Cawthorne 1987). None of these models can account for the excess. The most widely accepted solution to the soft X-ray excess problem is 'blobby' accretion as first proposed by Kuijpers & Pringle (1982). They suggested that soft X-rays could be produced by dense blobs of material which penetrate into the photosphere of the white dwarf, so that the shock was buried and the hard X-rays emitted by the shock are thermalised in the photosphere of the white dwarf with the energy eventually released as soft X-rays. This was developed further by Frank, King & Lasota (1988) (see also Litchfield & King 1990, Frank, King & Raine 2002). We also note that soft X-rays are produced near the base of the post-shock flow (Cropper, Wu & Ramsay 2000).

However, there is some uncertainty as to which energies the reprocessed component in the standard model is emitted. Heise & Verbunt (1988) found that in the 'reversed on-state' the UV and hard X-ray maxima were sometimes in anti-phase with the soft X-ray minima. They argued that the reprocessed component is emitted not as soft X-rays but in the extreme UV. In their scenario, any distinct soft X-ray component is due to 'blobs' of material.

Whilst *ROSAT* was suited to observing the soft X-ray component, its lack of sensitivity at higher energies meant that the spectral shape of the hard X-ray component was not well defined. Further, its energy resolution was modest. There is now a new generation of X-ray satellites which combine a high effective area, both at soft and harder X-ray energies and with higher spectral resolution.

We have undertaken a survey of polars using *XMM-Newton*. This survey contains observations of 37 polars – more than half of all known systems. A preliminary report of the work is given in Ramsay & Cropper (2003b) which also provides details of the programmatic aspects of the survey. A surprising large number of these systems were found to be in a low accretion state: these observations are described in Ramsay, Cropper & Wu (in prep). Detailed investigations into the phase resolved data of many of these systems have already been published (see Table 1 for details). This paper reports on the spectral energy distribution of those systems found to be in a high accretion state. We compare these with those results obtained using *ROSAT*.

2 OBSERVATIONS

XMM-Newton was launched in Dec 1999 by the European Space Agency. It has the largest effective area of any imaging X-ray satellite (Jansen et al 2001) and also has a 30 cm optical/UV telescope (the Optical Monitor, OM: Mason et al 2001) allowing simultaneous X-ray and optical/UV coverage. The EPIC instruments contain imaging detectors covering the energy range 0.15–10keV with moderate spectra resolution. Currently the EPIC pn detector (Strüder et al 2001) is currently better calibrated at lower energies compared to the EPIC MOS detector (Turner et al 2001). We therefore restrict the data used in this paper to the EPIC pn data. The observation log is shown in Table 1. By comparison with previous optical and X-ray data we conclude that all these systems were in high accretion states.

Source	Rev	Date	Reference
DP Leo	175	2000-11-22	1,2
WW Hor	181	2000-12-04	1,2
BY Cam	314	2001-08-26	3
EU Cnc	342	2001-10-21	
CE Gru	347	2000-10-31	4
RX J1007–2016	365	2001-12-07	5
EV UMa	366	2001-12-08	5
RX J1002–1925	367	2001-12-10	5
V895 Cen	403	2002-02-19	
V347 Pav	415	2002-03-16	6
HY Eri	419	2002-03-24	
RX J2115–58	421	2002-03-27	7
V349 Pav	438	2002-04-30	
AN UMa	438	2002-05-01	
EK UMa	442	2002-05-09	
GG Leo	444	2002-05-13	6
EU UMa	459	2002-06-12	6
EP Dra	523	2002-09-04	
V1500 Cyg	531	2002-11-02	
VY For	566	2003-01-10	
RX J1846+5538	566	2003-01-12	

Table 1. The sources discussed in the paper: we show the *XMM-Newton* orbital revolution and date the observations were made. The references to papers already published using these data are: (1) Ramsay et al (2001), (2) Pandel et al (2002), (3) Ramsay & Cropper (2002a), (4) Ramsay & Cropper (2002b), (5) Ramsay & Cropper (2003a), (6) Ramsay et al (2003), (7) Cropper, Ramsay & Marsh (2003).

The data were processed using the *XMM-Newton Science Analysis Software* (SAS) v5.3.3. Single and double events were extracted using an aperture of $\sim 40''$ centered on the source position. Background data were extracted from a source free region. The background data were scaled and subtracted from the source data. We used ready-made response files as appropriate for the filter used (generally 'thin').

3 SPECTRAL MODEL AND OTHER ASSUMPTIONS

In their analysis of *ROSAT* data, Ramsay et al (1994) and Beuermann & Burwitz (1995) used an emission model consisting of a single temperature blackbody for the reprocessed component and a single temperature thermal bremsstrahlung for the post-shock flow (since its temperature could not be well constrained by the data). The absorption component was a simple neutral absorption model. These model components were first approximations to that expected physically.

For this work we improve the model assumptions as follows. The emission from the hot post-shock region is evidently not a single temperature: the temperature is hottest near the shock front and the coolest near the base of the shock. Indeed, a large proportion of the emission generated in the *XMM-Newton* band will originate in the cooler, denser region near the photosphere of the white dwarf (Cropper, Wu & Ramsay 2000). To model this component we use the multi-temperature shock model of Cropper et al (1999). In reality the *reprocessed* component arising via irradiation by hard X-rays has a spectral signature more complex than a simple blackbody (cf Williams, King & Brooker 1987, Heise 1995). However, these more physical models are not available to us. Consequently, we retain the approximation of a blackbody. Lastly, the absorption is expected to be more complex than a neutral absorber (eg Done & Magdziarz 1998). If neutral absorption does not to give good fits then an additional absorption component is added, for instance a partial covering model.

In selecting the data to fit, we have excluded data which correspond to those orbital phases in which an absorption dip is clearly apparent (eg in CE Gru, Ramsay & Cropper 2002b). In addition we have excluded those phases in which the primary accretion region was not visible. For DP Leo, WW Hor and BY Cam, we have reprocessed the data using the more recent version of the SAS than was used by Ramsay et al (2001) and Ramsay & Cropper (2002a). The spectra were fitted using `XSPEC` (Arnaud 1996).

As noted earlier, the standard accretion shock model of Lamb & Masters (1979) and King & Lasota (1979) suggests that $L_{reprocessed}/L_{shock} \sim 0.5$, where L_{shock} is the total emission from the post-shock region and includes both $L_{X-hard,bol}$ and the cyclotron emission.

Here, we define the hard X-ray luminosity as ($L_{X-hard,bol} = 4\pi \mathrm{Flux}_{X-hard,bol} d^2$) where $\mathrm{Flux}_{X-hard,bol}$ is the unabsorbed, bolometric flux from the hard X-ray component and d is the distance. Since a fraction of this flux is reflected towards the observer (and our emission model takes into account the reflection of hard X-rays from the surface of the white dwarf), we switch the reflected component to zero after the final fit to determine the intrinsic flux from the optically thin post-shock region. We define the soft X-ray luminosity as ($L_{soft,bol} = \pi \mathrm{Flux}_{soft,bol} \sec(\theta) d^2$), where we assume that the soft X-ray emission is optically thick and can be approximated by a thin slab of material. The unabsorbed bolometric flux from the soft X-ray component is $\mathrm{Flux}_{soft,bol}$ and θ is the mean viewing angle to the accretion region.

4 RESULTS

4.1 Systems with no distinct soft X-ray component

There were several systems whose spectra could be well fitted using an absorbed multi-temperature shock model, without any requirement for an additional blackbody component. These are WW Hor, CE Gru, V349 Pav and V1500 Cyg. Table 2 gives their observed flux in both the 0.15-10keV and 0.1-2keV bands and also their unabsorbed bolometric fluxes.

In two systems (BY Cam and RX J2115–58) accretion at two different regions was observed, one which showed a soft X-ray component, while the other did not. It is interesting to note that both these systems are asynchronous polars (their spin period and orbital periods differ by a few percent). Ramsay & Cropper (2002a,b) suggest that a soft X-ray component is not seen in these systems because their reprocessed component is cooler compared to the other systems and therefore shifted to EUV or UV energies. We investigate this further in §9.

Source	Observed flux 0.15-10keV ergs s^{-1} cm^{-2}	Observed Flux 0.1-2.0keV ergs s^{-1} cm^{-2}	Flux unabs,bol ergs s^{-1} cm^{-2}
WW Hor	4.71×10^{-13}	1.73×10^{-13}	8.80×10^{-13}
BY Cam	5.35×10^{-12}	2.14×10^{-12}	9.03×10^{-12}
CE Gru	3.20×10^{-12}	1.02×10^{-12}	8.23×10^{-12}
RX J2115–58	7.79×10^{-12}	3.05×10^{-12}	1.33×10^{-11}
V349 Pav	1.27×10^{-12}	3.97×10^{-13}	2.64×10^{-12}
V1500 Cyg	7.64×10^{-14}	2.16×10^{-14}	1.41×10^{-13}

Table 2. The observed fluxes and unabsorbed, bolometric flux for systems observed using *XMM-Newton* which did not show any evidence for a distinct soft X-ray component: they could be fitted using a multi-temperature shock model. In the case of BY Cam and RX J2115–58, they showed one pole which did show a soft X-ray component and one which did not.

4.2 Systems with a distinct soft X-ray component

For those systems which did show both a hard and a soft X-ray component, we show in Table 3 the observed flux in both the 0.15–10keV and 0.1-2keV bands (to facilitate comparison with *ROSAT* observations). We also show the unabsorbed, bolometric fluxes from the individual model components and the soft-to-hard ratio (henceforth the 'ratio' for brevity) after converting the fluxes to luminosities (cf §3). We have not taken into account the geometrical correction to the soft component (which would *increase* the ratio) nor have we attempted to include an estimate of the cyclotron component (which would *decrease* the ratio). Further, we do not take into account reflection of hard X-rays from the surface of the white dwarf. We also show in Table 3 the ratio using a single temperature (30keV) thermal bremsstrahlung model for the hard component.

The most striking result is the number of systems which show low ratios. Out of the 17 systems which showed a distinct soft X-ray component (and modelled using the multi-temperature shock model), 7 have ratios less than 1.0 with another 5 systems having ratios between 1.0 and 2.0. Including those systems in Table 2 these numbers increase to 18 out of 23 systems having ratios less than 2. Once consideration of effects such as reflection of hard X-rays from the surface of the white dwarf, the correction for optical thickness effects and the cyclotron component are taken into account, these systems are likely to be consistent with the standard accretion model. Only 3 systems show ratios greater than 10 (DP Leo, RX J1007–2016 and EU UMa). We show this in histogram form in Figure 1a, where we include those systems which do not show a distinct soft X-ray component in the smallest ratio bin (therefore BY Cam and RX J2115–58 are 'counted twice').

Our survey using *XMM-Newton* data shows that only a small number of polars show a soft X-ray excess. How does this compare with the findings of Ramsay et al (1994) who used *ROSAT* data? Those authors define $L_{X-hard,bol} = 2\pi Flux_{X-hard,bol} d^2$, so we have re-determined the ratios using our definition of $L_{X-hard,bol}$ described in §3. Further, Ramsay et al applied a correction to take into account reflection from the white dwarf; applied a geometrical correction to the soft X-ray luminosity to account for viewing angle dependence and made an estimate of the cyclotron luminosity

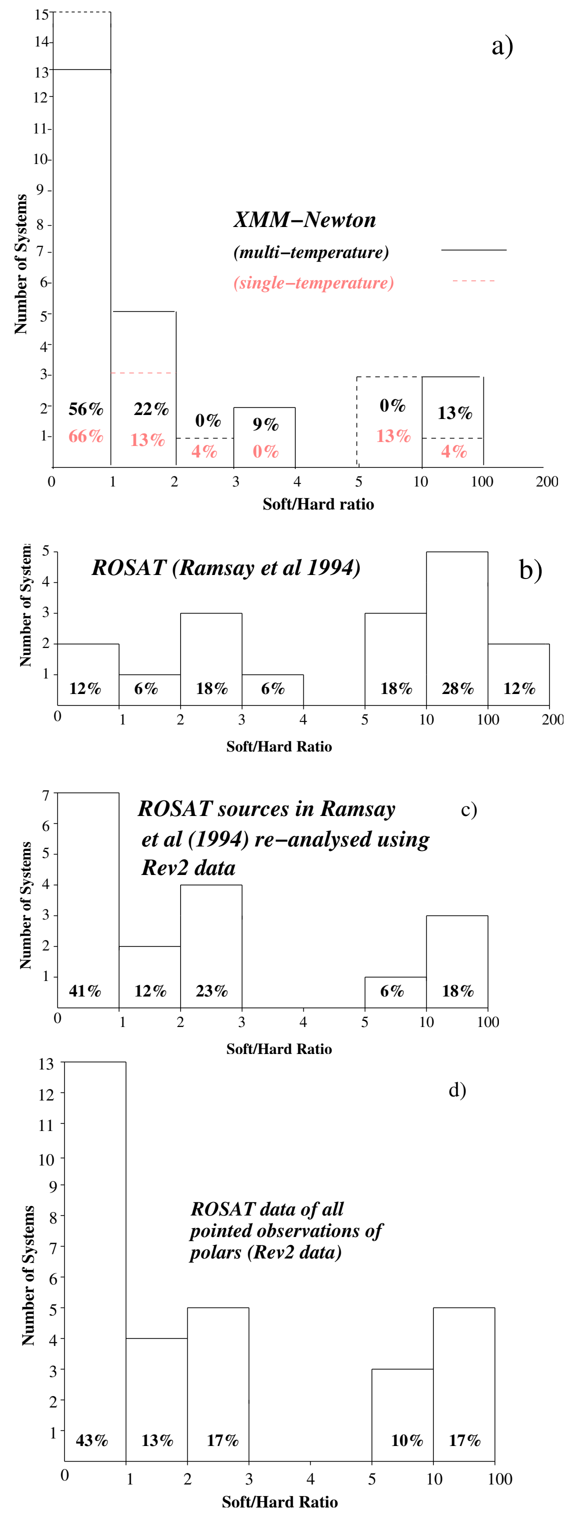

Figure 1. a): A histogram showing the distribution of the soft/hard ratio for the polars in a high accretion state in our *XMM-Newton* survey. We show the results when we use a multi-temperature model for the shock component and also a single temperature model. We include those systems (accretion poles) which do not show a distinct soft X-ray component. b): The distribution for those systems included in the *ROSAT* survey of high state systems as determined by Ramsay et al (1994). c) A histogram showing the distribution of the soft/hard ratio using *ROSAT* data for those systems included in the survey of Ramsay et al (1994) but re-analysed using Rev2 data. d) The energy ratio for all polars observed using the *ROSAT* PSPC in a pointed observation mode.

which was included in L_{shock}. To allow ease of comparison with *XMM-Newton* data and further *ROSAT* data later in the paper, we make corrections to the values reported in Ramsay et al (1994) as necessary. We show a histogram of the ratio of those systems included in the survey of Ramsay et al (1994) in Figure 1b. Compared to the results using *XMM-Newton* these ratios are rather striking: the ratios are more evenly spread with a bias towards higher ratios.

5 COMPARING THE *XMM-Newton* RESULTS WITH THOSE OF *ROSAT*

There are several possible reasons for the discrepancy. We examine the affect of the model which is used to fit the data and the intensity of the source. In addition, since the studies of Ramsay et al (1994) and Beuermann & Burwitz (1995) the calibration of *ROSAT* data is more mature: we revisit the available *ROSAT* data on polars to determine if we confirm the conclusions of these earlier studies.

5.1 The effect of the model used on the ratio

As noted before, in the *ROSAT* studies, the spectra were fitted using a simple absorbed blackbody plus single temperature thermal bremsstrahlung emission model. We have therefore fitted the *XMM-Newton* spectra using this model. We fix the temperature of the hard X-ray component at 30keV as was typically used in the *ROSAT* studies and add a Gaussian line near 6.7keV to account for any Fe Kα emission. We show in the last column of Table 3 the energy ratio using this model. We show the results in histogram form in Figure 1a which also shows the ratio using the multi-temperature model for the shock component.

Comparing the ratio using this single temperature shock model with that found using the multi-temperature shock model, we find that many systems show similar ratios. There appears to be no consistent tendency for one model to give ratios which are consistency larger or smaller than the other. Those systems giving larger differences, EU Cnc, EK UMa and EU UMa, can be accounted for, in the case of the first system, its comparative faintness, in the second the fact that a single temperature model gave a rather poor fit, and in the third system the ratio is very large so that even a small difference in the fitted absorption will affect the resulting unabsorbed, bolometric flux. We conclude that the model which is used to fit the X-ray data has, generally, a small effect on the resulting ratio.

Ramsay & Cropper (2003b) investigated the affect of adding a more complex absorption model (neutral absorption plus partial covering model) and found that this had a greater affect on the derived ratio compared with varying the emission model.

5.2 The effect of the accretion state on the ratio

We know that the ratio is dependent on the brightness of the system: using *ROSAT* observations of AM Her, the ratio was found to be significantly higher when it was brighter and BL Hyi showed higher ratios during flares (Ramsay, Cropper & Mason 1995). To further explore the effects of brightness level on the ratio, we extracted data from the

Source	Observed Flux 0.15-10keV ergs s^{-1} cm^{-2}	Observed Flux 0.1-2keV ergs s^{-1} cm^{-2}	Soft Flux unabs,bol ergs s^{-1} cm^{-2}	Hard Flux unabs,bol ergs s^{-1} cm^{-2}	$L_{s,\pi}/L_{h,4\pi}$ (MT)	$L_{s,\pi}/L_{h,4\pi}$ (ST)
DP Leo^R	3.74×10^{-13}	4.07×10^{-13}	8.42×10^{-12}	1.90×10^{-13}	11.1	8.3
BY Cam^{*R}	2.53×10^{-11}	1.10×10^{-11}	4.44×10^{-11}	4.43×10^{-11}	0.25	0.1
EU Cnc	7.90×10^{-15}	6.15×10^{-15}	6.13×10^{-14}	4.60×10^{-15}	3.3	0.4
RX J1007–2016^R	1.70×10^{-11}	2.04×10^{-11}	2.30×10^{-11}	5.74×10^{-13}	10.1	6.5
EV UMa	1.65×10^{-11}	8.46×10^{-12}	3.72×10^{-12}	2.63×10^{-11}	0.04	0.03
RX J1002–1925	1.81×10^{-12}	1.52×10^{-12}	1.00×10^{-11}	2.35×10^{-12}	1.1	0.3
V895 Cen^R	7.70×10^{-13}	6.89×10^{-13}	1.49×10^{-12}	3.17×10^{-13}	1.2	1.6
V347 Pav^R	1.65×10^{-11}	1.05×10^{-11}	6.93×10^{-11}	2.53×10^{-11}	0.7	1.1
HY Eri^R	1.36×10^{-12}	8.42×10^{-13}	2.67×10^{-11}	2.02×10^{-12}	3.3	2.3
RX J2115–58^{*R}	1.89×10^{-11}	8.14×10^{-12}	8.02×10^{-12}	3.93×10^{-11}	0.05	0.1
AN UMa^R	6.38×10^{-12}	6.12×10^{-12}	1.34×10^{-11}	6.07×10^{-12}	0.6	0.7
EK UMa^R	3.91×10^{-12}	3.58×10^{-12}	2.86×10^{-11}	5.20×10^{-12}	1.2	6.1
GG Leo^R	1.15×10^{-11}	4.14×10^{-12}	2.09×10^{-11}	3.03×10^{-11}	0.2	0.1
EU UMa^R	6.86×10^{-12}	1.37×10^{-11}	2.33×10^{-10}	5.09×10^{-13}	116	33
EP Dra	5.45×10^{-12}	2.15×10^{-12}	7.13×10^{-12}	1.30×10^{-11}	0.1	0.4
VY For	2.74×10^{-13}	2.53×10^{-13}	1.18×10^{-12}	1.62×10^{-13}	1.8	0.9
RX J1846+55^R	2.09×10^{-12}	1.05×10^{-12}	2.77×10^{-11}	3.78×10^{-12}	1.8	1.5

Table 3. The observed fluxes in the 0.15-10keV and 0.1-2.0keV bands using an absorbed blackbody plus multi-temperature model (MT) using *XMM-Newton* data. We also show the unabsorbed, bolometric fluxes (unabs, bol) derived for the soft X-ray and the hard X-ray components using a MT model. Those systems marked with a * were observed to have two accretion poles: one which showed a soft component and one which did not. These fluxes refer to the 'soft' pole. We show in the last two columns, the ratio of the luminosities derived using the MT model and also a model where we assume a single temperature (30keV) thermal bremsstrahlung model (ST) for the shock component. We have not taken into account the geometrical correction in determining the soft X-ray luminosity nor the cyclotron component or reflection of hard X-rays from the surface of the white dwarf. ^{R} refers to those systems which were observed using *ROSAT* in the PSPC pointed programme and in a high accretion state.

ROSAT archive for our *XMM-Newton* sources (those shown in Table 3). We extracted data in a similar way to that of our *XMM-Newton* data: namely, restricting the data to cover phase intervals covering the bright phase and excluding phases of absorption dips or eclipses. For simplicity, and make it easy for others to reproduce, we fit the spectra using an absorbed blackbody plus thermal bremsstrahlung of fixed temperature (30keV). We derived the observed flux in the 0.1–2.0keV band from both the *XMM-Newton* and *ROSAT* observations. We also determined the unabsorbed, bolometric luminosities of both the soft and hard X-ray components using these data and compute their ratio. We show the relationship between the brightness and the energy balance ratio in Table 4 and Figure 2. We find that when a given system is bright, the trend is for higher energy balance ratios. This is consistent with that found using the *ROSAT* data.

All subsets of a population can be biased. For instance, if one sample was biased towards less luminous polars then the results shown in Figure 2 imply that this sample would be biased towards lower ratios. In addition, a number of bright and well observed polars were not included in our *XMM-Newton* survey - eg AM Her, VV Pup, UZ For.

To investigate this further, we determined the bolometric X-ray luminosity of each system included in the *XMM-Newton* and *ROSAT* surveys. We used the best available distance estimate in the literature (for those systems where no distance estimate was available we assumed a canonical distance of 100pc). For brevity, we do not record the luminosities and distances for each system. Suffice to say, the mean bolometric X-ray luminosity for our *XMM-Newton* survey is 2×10^{32} ergs $s^{-1}$and for the *ROSAT* sample 3×10^{32} ergs s^{-1}. The mean luminosity of the *ROSAT* sample of Ramsay et al (1994) was 2×10^{32} ergs s^{-1}. This implies that the overall samples were not influenced in such a way that the intrinsic luminosity biased the resulting distribution of ratios (of course, this is not the case for any individual system).

We also compared the total luminosity of a system with its energy balance ratio. We find that there is no clear relationship between these quantities. This suggests that while an increase in the accretion rate will give a higher ratio for any given polar (assuming the accretion rate is proportional to the total X-ray luminosity), a given accretion rate will not produce a certain ratio in every system. There are clearly additional factors which influence the ratio.

5.3 The effect of the calibration on the ratio

The original studies of *ROSAT* data by Ramsay et al (1994), Beuermann & Burwitz (1995) and others, were made using 'Rev0' calibrated data. Further, the response files which were used were less definitive than currently available. *ROSAT* data have now been reprocessed several times, with 'Rev2' data now available in the public archives. In addition, for soft X-ray sources (thus including polars) a higher detector response was found compared to the original response files, while an excess was found at higher energies (cf calibration documents in the MPE web site). We have therefore retrieved all available *ROSAT* data of polars in the public archive. We extracted data in a similar manner to that described in §5.2.

Firstly, we consider those 17 sources reported by Ram-

Source	*XMM/ ROSAT* Flux	*XMM/ ROSAT* ($L_{s,\pi}/L_{h,4\pi}$)
DP Leo	0.2	0.3
BY Cam	1.3	0.5
RX J1007–2016	16.2	8.1
V895 Cen	0.5	3.2
V347 Pav	0.6	5.5
HY Eri	0.1	0.1
AN UMa	0.7	0.9
EK UMa	0.4	0.3
GG Leo	0.3	0.2
EU UMa	3.7	15.0
RX J1846+5537	0.6	0.8

Table 4. Those sources in our *XMM-Newton* survey which were also observed in the *ROSAT* PSPC pointed programme. We show the ratio of the flux observed using *XMM-Newton* compared to that found using *ROSAT*. We also show the ratio of the energy balance ratio determined using *XMM-Newton* and *ROSAT* (assuming a single temperature (30keV) component for the post-shock region).

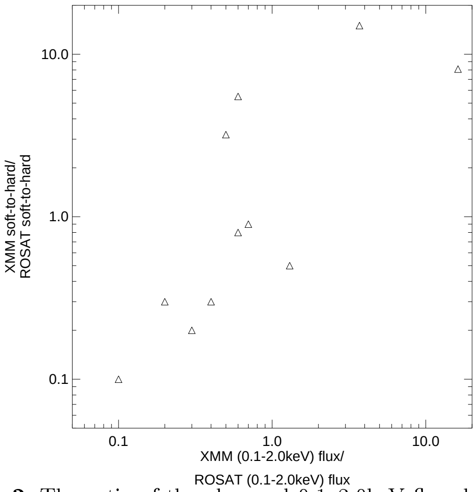

Figure 2. The ratio of the observed 0.1–2.0keV flux determined using *XMM-Newton* and *ROSAT* against the energy balance ratio determined using *XMM-Newton* and *ROSAT* for a given source.

say et al (1994) which were found to be in a high accretion state. Of those sources (7) in which upper limits were placed on the bremsstrahlung X-ray flux in Ramsay et al (1994), we now find, using Rev2 data, that the spectral fits are significantly worse if we do not include a thermal bremsstrahlung. We then compared the observed fluxes in the 0.1-0.4keV and 0.5-2.0keV bands derived using the blackbody and thermal bremsstrahlung components respectively and compared them directly with those fluxes reported by Ramsay et al (1994) (the spectral files used by Ramsay et al 1994 are not available). We then compared the ratio 0.1-0.4keV/0.5-2.0keV determined using Rev0 and Rev2 data (henceforth Rev0/Rev2).

There were 8 sources which were positioned off-axis: of these 5 had upper limits to the thermal bremsstrahlung flux over 0.5–2.0keV in the Rev0 analysis, while this component was required for a good fit using Rev2 data. The remaining three had a mean ratio Rev0/Rev2=2.0. Therefore, for off-axis sources, there is some indication that the soft X-ray flux was more prominent in the Rev0 data than in the Rev2 data. For the 9 on-axis source 2 had upper limits to the thermal bremsstrahlung flux in the 0.5-2.0keV band in the Rev0 data. For the remaining 7 sources, the situation is less clear with some systems having higher Rev0/Rev2 ratio while it was lower in others - the mean was 1.1. These results suggest that the energy balance determined using *ROSAT* data should be re-examined. (Ramsay & Cropper 2003b focused on *ROSAT* and *XMM-Newton* observations of AN UMa and found a much higher ratio using *ROSAT* data compared with *XMM-Newton* data. For the *ROSAT* analysis we used an inappropriate response file so that particular result in that paper should be disregarded).

We determined the observed flux in the 0.1–2.0keV band and the bolometric fluxes of the soft and hard X-ray components. We also compute the soft to hard luminosity ratio (cf §3). The results are shown in Table 5 and in histogram form in Figure 1c. It is clear that using the Rev2 data, the energy balance ratio is now biased towards lower ratios compared with those determined using Rev0 data and more like the *XMM-Newton* distribution.

We now include all those polars which were observed in a pointed PSPC observation and not included in the survey of Ramsay et al (1994): these results are also shown in Table 5 and in Figure 1d. Taken as a whole, the *ROSAT* observations of polars show a similar result to that found using our *XMM-Newton* data: the ratios are biased towards low values, with only $\sim$1/4 of systems showing high ratios (slightly more than found with our *XMM-Newton* data (Figure 1a)). We conclude that the reason why Ramsay et al (1994) found many systems to have a high ratios is due to the data being less well calibrated than is now possible.

6 THE STATUS OF THE SOFT X-RAY EXCESS IN POLARS

There is a general impression that there is a prevalent soft X-ray excess problem in polars. In his book '*Cataclysmic Variable stars*' (Warner 1995), Warner states '...lead to the conclusion that a soft X-ray excess does exist.'. Similarly, in their book '*Accretion Power in Astrophysics*', Frank, King & Raine (2002) claim that 'the $L_{[hard]}/L_{soft}$ is always found to be much smaller than [predicted]'.

We conclude from our *XMM-Newton* observations and from our re-analysis of *ROSAT* PSPC data that most (but not all) systems show a low soft/hard ratio. Once consideration of affects such as reflection of hard X-rays from the surface of the white dwarf, the correction for optical thickness effects and the cyclotron component are taken into account (we do not do this here as for many systems these corrections are unknown), most systems are likely to be consistent with the standard accretion model. A relatively small number of systems do, however, show a strong excess. This is in contrast to the earlier studies which showed that many systems had medium to high ratios.

As noted in our introduction, the most likely cause of the soft X-ray excess is blobs of material. This was called into question by Greeley et al (1999) who observed AM Her using the Hopkins UV telescope and found evidence for rapid vari-

Source	Start Date	Observed 0.1-2.0keV	Soft flux ergs s^{-1} cm^{-2}	Hard Flux ergs s^{-1} cm^{-2}	$L_{s,\pi}/L_{h,4\pi}$
BY Cam^{X}	1991-03-09	8.43×10^{-12}	3.47×10^{-11}	3.52×10^{-11}	0.2
V834 Cen^{XL}	1992-07-27	2.76×10^{-11}	6.98×10^{-11}	2.42×10^{-11}	0.7
EF Eri	1990-07-18	4.16×10^{-11}	3.45×10^{-11}	1.84×10^{-10}	0.05
UZ For^{XL}	1991-08-14	1.67×10^{-11}	2.84×10^{-11}	2.96×10^{-12}	2.4
AM Her	1991-04-12	3.37×10^{-10}	4.49×10^{-10}	1.16×10^{-10}	1.0
BL Hyi	1991-04-15	2.42×10^{-11}	1.89×10^{-10}	1.66×10^{-11}	2.9
DP Leo^{X}	1993-05-30	1.96×10^{-12}	6.48×10^{-12}	6.47×10^{-14}	25
VV Pup	1991-10-17	1.28×10^{-10}	1.90×10^{-10}	1.76×10^{-11}	2.6
AN UMa^{X}	1991-12-04	1.04×10^{-11}	2.24×10^{-11}	6.91×10^{-12}	0.8
EK UMa^{X}	1992-05-12	6.31×10^{-12}	9.12×10^{-12}	1.10×10^{-13}	21
QQ Vul	1991-04-12	6.28×10^{-12}	8.70×10^{-12}	6.35×10^{-12}	0.3
RS Cae^{XL}	1992-09-21	3.50×10^{-12}	1.46×10^{-11}	6.55×10^{-13}	5.5
RX J1007-2016^{X}	1992-11-17	1.58×10^{-12}	3.24×10^{-12}	1.02×10^{-12}	0.8
EU UMa^{X}	1993-05-25	3.66×10^{-12}	9.14×10^{-12}	1.06×10^{-12}	2.2
V347 Pav^{X}	1993-03-26	1.81×10^{-11}	3.77×10^{-11}	4.81×10^{-11}	0.2
QS Tel	1992-10-13	5.17×10^{-12}	1.32×10^{-11}	2.68×10^{-12}	1.2
HU Aqr	1993-10-27	4.09×10^{-11}	3.14×10^{-10}	1.04×10^{-10}	11
CV Hyi^{XL}	1993-11-03	1.30×10^{-13}	5.86×10^{-13}	1.37×10^{-13}	1.1
RX J0153–59^{XL}	1992-07-01	5.08×10^{-13}	1.12×10^{-12}	1.92×10^{-12}	0.2
AI Tri	1993-07-19	1.79×10^{-12}	8.58×10^{-12}	3.05×10^{-12}	0.7
HY Eri^{XL}	1992-02-24	6.68×10^{-12}	9.35×10^{-10}	$<4.34\times10^{-13}$	>58
RX J0803-47	1991-12-03	1.59×10^{-12}	3.20×10^{-11}	$<1.54\times10^{-13}$	>53
MN Hya^{XL}	1994-06-01	3.80×10^{-13}	6.87×10^{-12}	5.58×10^{-12}	0.3
V381 Vel	1993-11-30	9.14×10^{-13}	5.51×10^{-12}	2.28×10^{-12}	6.0
FH UMa^{XL}	1993-05-12	3.15×10^{-13}	1.56×10^{-12}	$<7.36\times10^{-14}$	>5.3
V884 Her	1993-09-11	1.19×10^{-11}	6.30×10^{-11}	7.56×10^{-12}	2.1
V895 Cen^{XL}	1997-02-12	1.30×10^{-12}	5.09×10^{-12}	3.23×10^{-12}	0.5
GG Leo^{X}	1993-11-09	1.47×10^{-11}	4.33×10^{-11}	2.11×10^{-11}	0.5
RX J1846+5537^{X}	1992-06-15	1.76×10^{-12}	2.40×10^{-11}	3.14×10^{-12}	1.9
V1432 Aql	1993-03-31	9.08×10^{-12}	7.86×10^{-11}	4.66×10^{-11}	0.4

Table 5. The log of all pointed *ROSAT* PSPC observations of polars. The date shown is the start date of the observations. We show the observed flux in the 0.1-2.0keV band as well as the bolometric luminosity derived from the soft X-ray and hard X-ray components. We model the spectra using an absorbed blackbody plus thermal bremsstrahlung component (kT=30keV). The top panel gives those polars contained in the work of Ramsay et al (1994), while the bottom panel were not. The ^{X} refers to those systems which were part of our *XMM-Newton* survey and in a bright state (Table 3), while ^{XL} refers to those systems which were part of our *XMM-Newton* survey and in a low accretion state (Ramsay, Cropper & Wu, in prep).

ations in flux. They suggested their observations were not consistent with the blobby accretion model: they determined the average density of the flares assuming that the mass in the flare was deposited over the extent of the UV hot-spot. This was much less than the minimum density required for a 'blob' of material to form a buried shock below the photosphere of the white dwarf. However, King (2000) argued that the data are consistent since Greeley et al (1999) assumed that the area over which accretion occurs (A_{acc}), and the total area over which the reprocessed emission emerges (A_{eff}) are the same, while in actual fact, $A_{acc} << A_{eff}$. Therefore, King (2000) concludes that blobby accretion is still the most viable solution to account for the soft X-ray excess. We now go on to determine whether there is any common factor for those, relatively few, systems which show a high ratio.

7 WHY A HIGH RATIO?

7.1 Orbital Period

There are 3 systems which show high ratios using *XMM-Newton* data: DP Leo, RX J1007-2016 and EU UMa. Further, using *ROSAT* data there were 5 systems showing high ratios: DP Leo, EK UMa, HY Eri, RX J0803–47 and HU Aqr. It is clear that the orbital period is not a factor in determining the ratio: DP Leo and EU UMa have orbital periods of ∼90 mins while RX J1007–2016 has a period of 208 mins.

7.2 Magnetic Field

The second parameter which we consider is the magnetic field strength. RX J1007-2016 with a high ratio has a magnetic field of ∼90 MG (Reinsch et al 1999), while DP Leo has a magnetic field strength of 31MG for its primary (X-ray emitting) accretion pole (Cropper & Wickramasinghe 1993). There is no estimate for the field strength of EU UMa in the literature. However, systems which show sim-

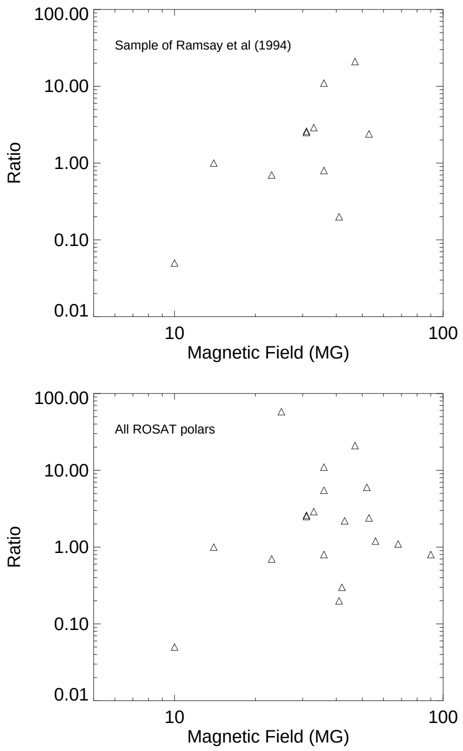

Figure 3. The energy balance ratio as a function of magnetic field strength for those systems in the study of Ramsay et al (1994) (left), and all those polars observed in the pointed mode (Rev2 data was used).

ilarly high magnetic field strengths also show low ratios: for instance, BY Cam (41MG), AN UMa (36MG) and EK UMa (47MG). This is in contrast to the results of Ramsay et al (1994) who found a trend between the ratio and the magnetic field, with systems with low magnetic fields tending to have low ratios. We show in Figure 3 the ratio derived using Rev2 *ROSAT* data against magnetic field strength for those systems in the sample of Ramsay et al (1994) which had magnetic field estimates: this shows a rather weak trend. We also show these values using all systems observed using *ROSAT*: the complete *ROSAT* sample shows no evidence of a trend. We conclude that the trend of energy balance ratio against magnetic field was largely due to the small sample which was used.

7.3 The coupling radius and stream field orientation

A third parameter which may affect the ratio is the point at which the accretion flow feels the force of the magnetic field of the white dwarf: the coupling radius, R_c. Although the location of this point is difficult to determine theoretically, we use the same relationship as was used by Ramsay et al (1994):

$$R_c = r_\mu \cos^2(\beta) = \cos^2(\beta) 5.1 \times 10^8 M_1^{-1/7} \dot{M}_{16}^{-2/7} \mu_{30}^{4/7} \text{ cm}$$

where β is the angle between the spin and magnetic axis and the other parameters their usual meanings. Since the mass transfer rate is generally poorly known (being dependent on distance) we take the observed orbital period-mass transfer rate to set this parameter (Warner 1995). For magnetic field strengths we use the value in Wickramasinghe & Ferrario (2000), or when not known we assume B=20MG. For the mass of the white dwarf we take the values from the literature or assume M_{wd}=0.7$M_\odot$ when not known. We find that the energy balance ratio determined using *XMM-Newton* data is not correlated with R_c. This is in contrast to Ramsay et al (1994) who found using the Rev0 *ROSAT* data that low ratio systems tended to have small coupling radii, and high ratio systems tended to have large coupling radii. We conclude this trend was probably due to chance, although we discuss below the reasons why β may play some role in determining the resulting X-ray spectrum.

The angle β may also affect the characteristics of the accretion flow and therefore the X-ray spectrum. If β is at high angles, the accretion flow travels further before feeling the effect of the magnetic field. This may influence the resulting X-ray spectrum. Unfortunately, this value is not well known for many systems. However, DP Leo has $\beta = 103°$, EK UMa $\beta = 56°$ (Cropper 1990) and both show high ratios. In contrast, HU Aqr, has a relatively small dipole offset ($\beta = 16°$, Schwope et al 2001), but shows a high ratio (although smaller than DP Leo and EK UMa). Clearly, polarimetric observations of the other systems showing high ratios (HY Eri and RX J0803–47) are encouraged so that their accretion geometry can be determined.

We now consider the angle that the accretion stream makes with the magnetic axis at the point where it couples onto the magnetic field of the white dwarf. The azimuth of the magnetic axis tends to point ahead of the line center joining the binary components, with a mean angle of $\sim 20°$ (Cropper 1988). In contrast, the coupling point is known to vary from cycle to cycle and is related to the accretion rate (eg Bridge et al 2002, 2003). Small changes in the coupling point could make large changes to the angle that the stream makes with the magnetic axis. Could this affect the resulting X-ray spectrum? The asynchronous polars have a changing stream-magnetic field orientation, repeating once every beat period. We observed two of them – RX J2115–58 and BY Cam. We find that they both show one pole which shows a distinct soft X-ray component and one pole which does not. This implies that the stream-field orientation does have an affect on the resulting X-ray spectrum. We have *XMM-Newton* observations of RX J2115–58 which were made at 7 different stream-field orientations. A brief summary of these observations are reported by Cropper, Ramsay & Marsh (2003). Detailed work is in progress to determine how this orientation affects the resulting X-ray spectra and the resulting energy balance ratio.

8 SHORT TIME VARIABILITY

We now investigate if the degree of variability in soft X-rays is related to the energy balance ratio. Simple considerations suggest that systems with high ratios may be expected to show enhanced soft X-ray variability since the most likely physical mechanism for producing the soft X-ray excess is that of dense blobs of material (Kuijpers & Pringle 1982).

We extracted events in the energy range 0.15–0.5keV (since the soft component lies in this band) from a narrow radius around the source – again excluding faint phases,

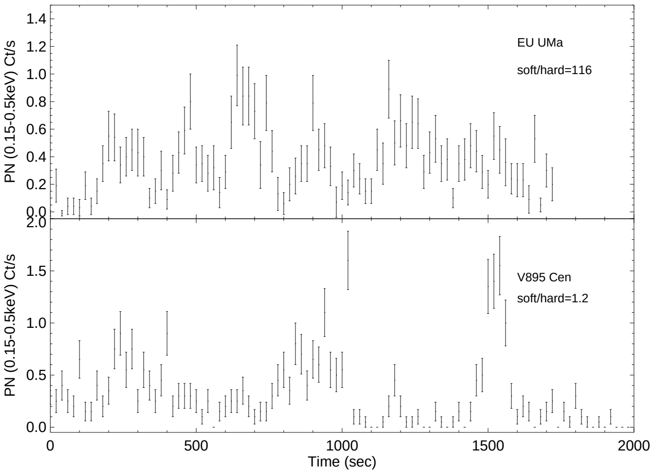

Figure 4. The 0.15-0.5keV band light curves of EU UMa, which has a high energy balance ratio, and V895 Cen, which has a low energy balance ratio. Both systems show prominent flickering or flaring behaviour.

absorption dips or eclipses. There are various techniques to measure the variability of an object: we now discuss several of these.

Although a weak test of source flickering behaviour, we first performed a Discrete Fourier Transform of these events. There was no correlation between the power spectrum (for instance the frequency at which there was an upturn in power) and the energy ratio which we measured earlier. Secondly, we determined the time between events and divided this time by the mean time separation of events (to account for the brightness of the source) and made a histogram of this time difference. Again there was no correlation between the shape of the histograms and the energy ratio.

We then binned the event rate files into 10 sec bins and then measured the mean and the standard deviation of these light curves. In those systems where there was a trend in the light curve, we remove this trend using a polynomial fit. We find no correlation between the standard deviation and the energy balance ratio. We also compared the expected variation in the light curve, σ_e, with that measured, σ_o: the more variable the source the higher the ratio σ_o/σ_e (Sokoloski, Bildstein & Ho 2001). This was done for various bin sizes: we find no trend with the energy balance ratio.

Flickering or flaring behaviour is seen in many polars. However, we find that the degree of flaring does not necessarily affect the resulting X-ray spectrum. We show in Figure 4 a section of the 0.15–0.5keV light curves of EU UMa (energy balance ratio 116 using *XMM-Newton*) and V895 Cen (energy ratio 1.2): both systems show flaring behaviour but very different ratios. Therefore, in systems which show prominent flares or flickering behaviour, but low energy balance ratios, the flares are likely to be due to enhancements in the accretion flow, but which do not have sufficient density to penetrate the photosphere of the white dwarf and therefore have buried shocks.

9 SYSTEMS WITH NO SOFT X-RAY COMPONENT

Until now, one of the defining characteristics of polars has been the presence of a strong soft X-ray component. It is therefore surprising that we find 6 systems which showed at least one accretion pole which did not show a distinct soft X-ray component at all. It is possible that the reprocessed component is cool enough to have moved out of the *XMM-Newton* band as proposed by Heise & Verbunt (1988).

If this is the case then this may be reflected in the observed 0.15-0.5keV to UV flux ratios: for those systems which show no distinct soft X-ray component this ratio should be lower than in those systems which do. Firstly, we simulated the spectrum of a polar which had an energy balance consistent with that predicted by the standard model, with the temperature of the reprocessed component being in the range 3–65eV. We include in our model an unheated white dwarf of mass $0.7M_{\odot}$(and assume the Nauenberg 1972 mass-radius relationship) and temperature 20000K (1.7eV) assuming a blackbody. We also include a thermal bremsstrahlung component with temperature 30keV. We then measured the expected flux in the 0.15–0.5keV band and in the UVW1 (an effective wavelength of 2910Å) and UVW2 (2120Å) OM filters. We show the ratios for two values of absorption in Figure 5 and tabulate the measured soft X-ray/UV ratios of our sample of *XMM-Newton* polars in Table 6. Obviously this does not take into account viewing angle affects or stream emission: for significant stream emission these ratios would be greater.

To convert the observed count rate to flux we use the latest conversion factor assuming a white dwarf spectrum: 1 ct/s in UVW1 implies a flux of 4.4×10^{-16} ergs s^{-1} cm^{-2}Åwhile 1 cts/s in UVW2 gives 5.8×10^{-16} ergs s^{-1} cm^{-2}Å. There are some systems in which the source was not detected in either UV filter (EU Cnc) or was not detected in both (or only one UV filter was used). In the case of BY Cam and RX J2115–58 (which showed one pole which did not show a distinct soft component) we used the appropriate phase range.

For those systems with a distinct soft X-ray component, the 0.15-0.5keV/UV ratios are generally high, while in contrast, those systems which do not show a distinct soft component, generally show lower ratios. Indeed, many of the soft X-ray systems show ratios which are much higher than the results from the simulation. If the temperature of the white dwarf in these systems is hotter than 20000K the ratios will be higher: for a blackbody of temperature 40000K, the 0.15–0.5keV/UV ratios increase by a factor of 3.5, while for a temperature of 60000K they increases by a factor of 56. Further, if the system shows a high soft X-ray excess, or has a significant UV stream component then this will be reflected in high 0.15-0.5keV/UV ratios.

Of the 'soft' X-ray systems only VY For shows a relatively low ratio. It is not clear why this is the case – fitting its X-ray spectrum does not show a particularly high absorption. It is interesting to note, however, that Beuermann et al (1989) and Cropper (1997) suggested that its main accretion pole is hidden from view and the visible pole was the secondary pole. In a sample such as ours we may expect more than one system to have a 'hidden' pole.

Care should be taken when interpreting these results

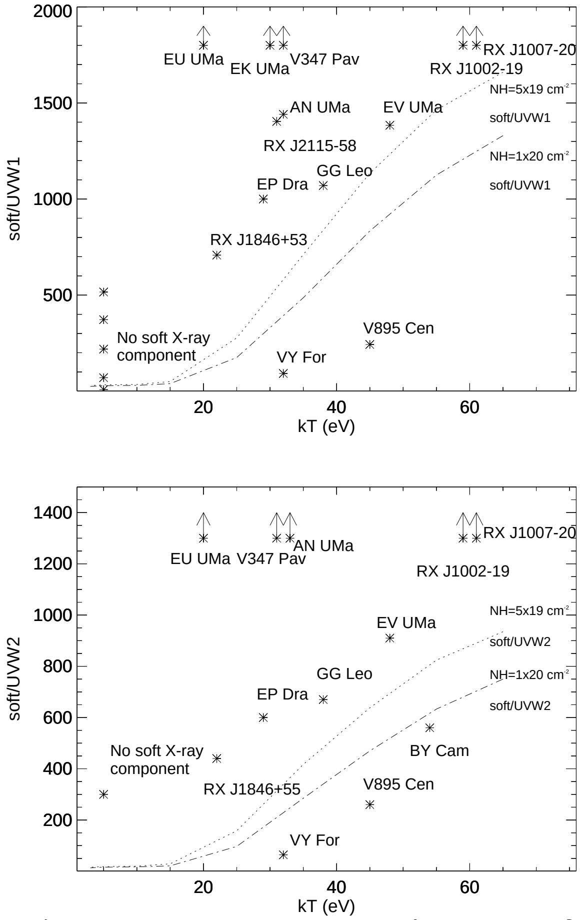

Figure 5. We show the simulations of the expected flux ratios 0.15-0.5keV/UVW1 and 0.15-0.5keV/UVW2 assuming a black-body of various temperature and a shock component of 30keV. Their normalisations are set so that the unabsorbed, bolometric luminosities give a ratio consistent with the standard accretion model. We also include a blackbody component of temperature 20000K to account for a white dwarf of mass $0.7M_{\odot}$. We plot the best fit blackbody temperatures derived from the X-ray spectra of each polar which has a soft X-ray component and their 0.15-0.5keV/UV ratios. For those systems showing no soft component we plot them, arbitrarily at kT=5eV.

since, as we pointed out above, we assume stream emission does not contribute to the UV flux and we do not take into account optical thickness affects. However, we find that overall, those systems which do not show a distinct soft X-ray component give lower (0.15-0.5keV)/UV flux ratios, consistent with our view that the reprocessed component has been shifted from soft X-ray energies to UV energies.

In the scenario of Heise & Verbunt (1988), those systems which show a soft X-ray component are accreting (at least some) dense blobs of material. However, for most polars we find that the energy balance is consistent with the standard accretion model – which does contain a significant contribution from dense blobs. Therefore, Heise & Verbunt (1988) are not correct in saying that a soft X-ray component *requires* blobs.

The factors that may affect the temperature of the soft component are M_{wd} (since that sets the maximum temperature in the shock), $\dot{M}$ (since this sets the height of the shock)

Source	0.15–0.5keV/ UVW1	0.15–0.5keV/ UVW2
CE Gru	520	300
V349 Pav	220	
V1500 Cyg	10	
BY Cam	70	
RX J2115–58	370	
BY Cam		810
RX J1007–2016	7800	4400
EV UMa	1400	910
RX J1002–1925	2600	1800
V895 Cen	240	260
V347 Pav	3600	1800
RX J2115–58	1400	
AN UMa	1400	1700
EK UMa	15000	
GG Leo	1100	670
EU UMa	610	3000
EP Dra	1000	600
VY For	90	64
RX J1846+53	710	440

Table 6. The observed flux ratios 0.15–0.5keV/UVW1 and 0.15–0.5keV/UVW2 for systems which did not show a distinct soft X-ray component (top) and those which did (bottom).

and the magnetic field strength (since this sets amount of cooling due to cyclotron radiation).

10 CONCLUSIONS

Our survey of polars using *XMM-Newton* has shown that most systems have X-ray spectra which give relatively low soft-to-hard X-ray ratios. This is in contrast to the results of Ramsay et al (1994) who used Rev0 *ROSAT* data and found that the energy balance ratio was biased towards high ratios. We have re-examined all the polars observed in the pointed mode using the *ROSAT* PSPC. Using Rev2 calibrated data we find that the energy ratio has a similar distribution to that of the *XMM-Newton* sample, with only a slight increase in the relative number of systems having a high ratio. We conclude that the results of Ramsay et al (1994) which showed many systems had high ratios were due to their data being less well calibrated than is now possible.

We show the distribution of the soft-to-hard ratio using the combined *XMM-Newton* and *ROSAT* samples in Figure 6. Most systems show low ratios: once consideration of affects such as reflection of hard X-rays from the surface of the white dwarf, the correction for optical thickness effects and the cyclotron component are taken into account, most systems are likely to be consistent with the standard accretion model. However, there are still a number of systems which show large excesses. We have explored the physical reasons for such an excess and speculate that the orientation between the magnetic field axis and the stream as it meets the magnetic field of the white dwarf may be a likely parameter.

We find that systems show ratios which are related to their intensity: when an individual systems is bright it shows a higher ratio. However, we find no evidence that their actual

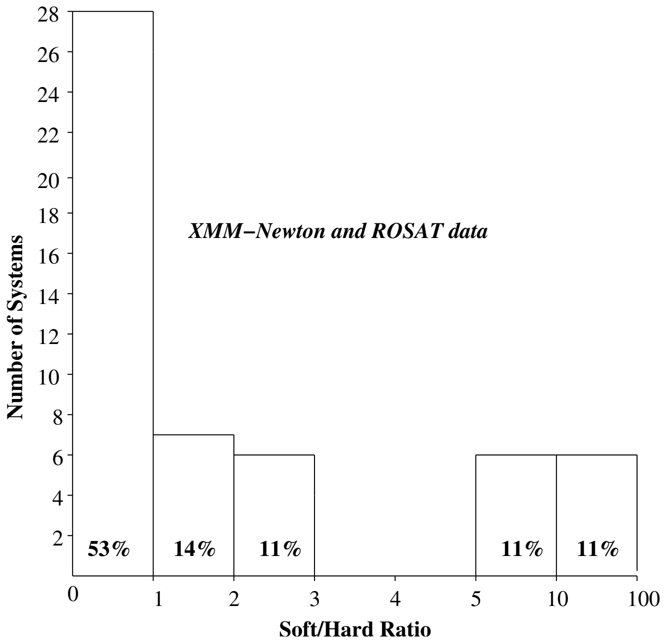

Figure 6. The soft/hard ratio for the source included in our *XMM-Newton* survey and all the polars which were observed in the *ROSAT* PSPC pointed programme.

luminosity sets the ratio, so that more luminous systems can have the same ratio as less luminous systems.

Another surprising finding from our survey is the number of systems which do not show any distinct soft X-ray component. We suggest that this is due to the reprocessed component being shifted to lower energies and hence out of the *XMM-Newton* X-ray window. Further study of what determines the temperature of the reprocessed component is strongly encouraged.

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