XMM-Newton observations of the eclipsing polar V2301 Oph

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ABSTRACT

We present XMM-Newton observations of the eclipsing polar V2301 Oph which cover nearly 2.5 binary orbital cycles and 2 eclipses. This polar is believed to have the lowest magnetic field strength (7 MG) of any known polar. We find evidence for structure in the X-ray eclipse profile which shows a ‘standstill’ feature lasting 26±4 sec. This allows us to place an upper limit on the mass of the white dwarf of ∼1.2 M⊙. We find no evidence for QPOs in the frequency range 0.02-10 Hz. This coupled with the absence of QPOs in RXTE data suggest that, if present, any oscillations in the shock front have a minimal effect on the resultant X-ray flux. We find no evidence for a distinct soft X-ray component in its spectrum - it therefore joins another 7 systems which do not show this component. We suggest that those systems which are asynchronous, have low mass transfer rates, or have accretion occurring over a relatively large fraction of the white dwarf are more likely to show this effect. We find that the specific mass transfer rate has to be close to 0.1 g cm⁻² s⁻¹ to predict masses which are consistent with that derived from our eclipse analysis. This maybe due to the fact that the low magnetic field strength allows accretion to take place along a wide range of azimuth.

Key words: Stars: individual: – V2301 Oph – Stars: binaries – Stars: cataclysmic variables – X-rays: stars

1 INTRODUCTION

Polars are binary systems in which the accreting white dwarf has a sufficiently high magnetic field strength to prevent the formation of an accretion disc. The magnetic field strength of the white dwarf lies in the range ∼7-200MG. The system with the lowest magnetic field strength is believed to be the eclipsing system V2301 Oph (Ferrario et al 1995).

V2301 Oph has been observed in X-rays using ROSAT, where it was bright in X-rays and showed a relatively hard spectrum (Ramsay 1997, Hessman et al 1997); RXTE (Steinman-Cameron & Imamura 1999) and ASCA (Terada et al 2004). In the optical band a bright accretion stream is evident and there is a significant cycle-to-cycle variation in its eclipse profile. Reynolds et al (2005) suggest that this variation is due to a change in the amount of material in the threading region, the point at which the accretion stream feels the force of the magnetic field of the white dwarf.

Because V2301 Oph is bright in X-rays and also an eclipsing binary (113 min, Silber et al 1994) it is an excellent source to study the accretion process in polars.

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2 OBSERVATIONS AND DATA REDUCTION

V2301 Oph has been observed using XMM-Newton on 5 separate occasions. The first 4 planned observations were compromised by high background radiation, which resulted in the observations not being carried out, or exposures which were short: we do not consider these observations further. However, the observation which took place on Sept 2004 was not affected by high background radiation. The details of the exposure time in the different instruments are shown in Table 1. The EPIC MOS (Turner et al 2001) start time is earlier (and the observations slightly longer) than that of the EPIC-pn (Strüder et al 2001). Observations with the Optical Monitor (Mason et al 2001) were carried out in fast mode and in two filter bands: the V-band, and UVW1 (2400–3400 Å) band. In the optical the mean brightness was...
The peak count rate in the EPIC pn detector is ~10 ct/s in the 0.15-10keV band, making V2301 Oph one of the brightest of polars in this band. Approximately 2.5 orbital cycles and two eclipses were observed (Figure 1). X-ray flux is seen throughout the orbital cycle, implying that at least one accretion region is seen at all times.

We show the light curves folded on the ephemeris of Barwig et al (1994) (after placing it onto TT) in Figure 2. As already noted by Hessman et al (1997), a dip is seen in the X-ray light curve at $\phi=0.9$ which is thought to result from the accretion stream obscuring the bright accretion region – this is manifest in the softness ratio which becomes significantly harder at this phase. A short dip is also seen in the unfolded UV light curve at this phase (Figure 1).

After the eclipse, at $\phi \sim 0.3-0.4$, the softness ratio becomes significantly softer. This could be due to one of the accretion regions having rotated out of view, with the region which is still visible having a much softer X-ray spectrum. The UV light curve shows a quasi-sinusoidal light curve and is likely to be due to the result of one or more hotter areas on the white dwarf surface rotating in and out of view.

### 3.2 The ephemeris

To calculate the time of mid-eclipse we determined the time of the start of the steep decline in the X-ray flux by eye.

### Table 1. The summary for XMM-Newton observations of V2301 Oph taken in 2004 Sept 6.

| Instrument | Mode       | Filter | Duration |
|------------|------------|--------|----------|
| EPIC MOS   | Small window | Thin   | 18657 s  |
| EPIC PN    | Large window | Thin   | 16657 s  |
| RGS        | Spectro + Q |        | 18885 s  |
| OM         | Fast Mode   | V      | 4399 s   |
| OM         | Fast Mode   | UVW1   | 13000 s  |

$V=17.5$, indicating it was in a relatively high accretion state – its observed range is $V \sim 16-21$ (Warner 1999).

The data were reduced using SAS v7.0. Only X-ray events which were graded as PATTERN=0-4 and FLAG=0 were used. Events were extracted from a circular aperture centered on the source, with background events being extracted from a source free area. The background data were scaled to give the same area as the source extraction area and subtracted from the source area. The events in the EPIC pn detector were slightly piled-up during the time intervals which had the greatest count rate. Since the MOS detectors were operating in small window mode, the MOS data were not piled-up. The RGS data were reduced using rgsproc and the first order spectra from the two RGS detectors were extracted. The OM data were reduced using omfchain.

3 THE LIGHT CURVES

3.1 General Features

The peak count rate in the EPIC pn detector is ~10 ct/s in the 0.15-10keV band, making V2301 Oph one of the brightest of polars in this band. Approximately 2.5 orbital cycles and two eclipses were observed (Figure 1). X-ray flux is seen throughout the orbital cycle, implying that at least one accretion region is seen at all times.

We show the light curves folded on the ephemeris of Barwig et al (1994) (after placing it onto TT) in Figure 2. As already noted by Hessman et al (1997), a dip is seen in the X-ray light curve at $\phi=0.9$ which is thought to result from the accretion stream obscuring the bright accretion region – this is manifest in the softness ratio which becomes significantly harder at this phase. A short dip is also seen in the unfolded UV light curve at this phase (Figure 1).

After the eclipse, at $\phi \sim 0.3-0.4$, the softness ratio becomes significantly softer. This could be due to one of the accretion regions having rotated out of view, with the region which is still visible having a much softer X-ray spectrum. The UV light curve shows a quasi-sinusoidal light curve and is likely to be due to the result of one or more hotter areas on the white dwarf surface rotating in and out of view.
3 and the end of the steep increase in X-ray flux. We defined the mid-point of these times as the time of mid-eclipse – we report these times in Table 2.

Compared to the ephemeris of Barwig et al (1994), the mid-point of the eclipses are earlier by 20–25 sec. To determine if there has been a systematic change in the arrival time of the eclipse, we obtained all the eclipse times from the literature. Some of these timings were not accurate enough to include and there appeared to be some typographical errors in 2 timings (the 5th and 6th timings reported in Steiman-Cameron & Imamura 1999). We corrected each time so that they were on the TT time system (ie including the shift from UTC to TAI and the appropriate number of leap seconds).

We used the ephemeris of Barwig et al (1994) (after placing it onto TT) to phase the eclipse times and the residuals are shown in the upper panel of Figure 3.

To determine if we could derive an improved ephemeris, we fitted all the eclipse times with a linear ephemeris and also an ephemeris with a quadratic term. Using these ephemerides we calculated the goodness of fit for each using the chi-squared estimator. In many of the previous eclipse time studies we had to estimate the uncertainty in the mid-eclipse time since they were not explicitly stated. The goodness of fit using the Barwig et al (1994) ephemeris was \( \chi^2_{\nu} = 7.1 \) (21 dof); using our linear ephemeris the fit was \( \chi^2_{\nu} = 5.23 \) (21 dof); and using our quadratic ephemeris the fit was \( \chi^2_{\nu} = 1.17 \) (20 dof). Our quadratic ephemeris:

\[
T_{\text{eclipse}} (TT) = 2448071.020690(61) + 0.0784500274(44) - 3.18(62) \times 10^{-13} E^2
\]

gives a better fit than our linear ephemeris with a confidence level of greater than 99.9%. The quadratic term could be due to an intrinsic change in the orbital period, an asynchronicity between the orbital period and the spin period of the white dwarf or a secular shift in the location of the accretion region(s) on the white dwarf. We note that the magnitude of the quadratic term is similar to that observed in HU Aqr, Schwope et al (2001), who suggested that the quadratic term seen HU Aqr was due to a shift in the location of the X-ray emission regions on the surface of the white dwarf.

### 3.3 The eclipse

In Figure 4 we show the X-ray light curve in 4 energy bands where we have folded the light curves on our quadratic ephemeris. The descent into eclipse is very rapid (<5 sec) which is followed by a ‘standstill’ lasting 26±4 sec (determined by eye) in the light curves made using photons with energies greater than 0.5keV. This is likely due to one accretion region, and then a second, being eclipsed by the secondary star. The UV light curve does not show this feature. After the eclipse of the second accretion region there is a rapid (<5 sec) descent into total eclipse. During the eclipse egress (which lasts 23±2sec), there is no evidence for a standstill.

As far as we can determine, this is the first time that such a standstill has been observed in the X-ray light curve.
We find that this sets an upper limit on the mass of the white dwarf, $M$, for white dwarfs. We trace the Roche potential out of the binary system along the line of sight from any point in the vicinity of the white dwarf. As a starting point we take the results of an analysis of optical observations of the AM Her systems if the accretion shock front is not stable (eg Saxton & Wu 1999, Mignone 2006 and references therein).

It is predicted that Quasi Periodic Oscillations (QPOs) may occur on a timescale of a few seconds in the light curves of AM Her systems (Perryman et al 2001) and SDSS J015543.40+002807.2 (O’Donoghue et al 2006). If X-rays from the accretion regions are emitted close to the surface of the white dwarf, $M$, and 1.0 ($M_{\odot}$), we find that we can reproduce the observed duration of the standstill feature. Further, both accretion regions reappear simultaneously after eclipse (and hence no standstill is observed) if the accretion regions are located at ($90^\circ$, $10^\circ$) and ($60^\circ$, $45^\circ$) where the co-ordinates are $\beta, \xi$ (as defined by Cropper 1989). The shape of the accretion regions are expected to be more complex than simple circular regions, but we have found a solution which is self consistent and in agreement with the results of Reynolds et al (2005).

### 3.4 Searching for QPOs

It is predicted that Quasi Periodic Oscillations (QPOs) may be seen on a timescale of a few seconds in the light curves of AM Her systems if the accretion shock front is not stable (eg Saxton & Wu 1999, Mignone 2006 and references therein).

| Mid-Eclipse (TT) | Error (Days) | Reference |
|------------------|--------------|-----------|
| 2448432.98940    | 0.00023      | (1)       |
| 2448806.48947    | 0.00007      | (2)       |
| 2448806.56813    | 0.00007      | (2)       |
| 2448806.64653    | 0.00007      | (2)       |
| 2448807.59525    | 0.00007      | (2)       |
| 2448808.60768    | 0.00007      | (2)       |
| 2448809.39228    | 0.00007      | (2)       |
| 2449569.41619    | 0.00006      | (3)       |
| 2449571.45579    | 0.00006      | (3)       |
| 2449572.39725    | 0.00006      | (3)       |
| 2449572.55411    | 0.00006      | (3)       |
| 2449573.41705    | 0.00006      | (3)       |
| 2449573.49547    | 0.00006      | (3)       |
| 2450220.86502    | 0.00005      | (4)       |
| 2450221.80644    | 0.00005      | (4)       |
| 2450595.77751    | 0.00009      | (4)       |
| 2450601.73976    | 0.00005      | (4)       |
| 2451661.67783    | 0.00005      | (5)       |
| 2451662.61923    | 0.00005      | (5)       |
| 2451663.69623    | 0.00005      | (6)       |
| 2452545.68332    | 0.00006      | (6)       |

Table 2. The observed times for the mid-eclipse of V2301 Oph. To ensure the times are on a common reference frame, we assume a Roche Lobe solution which is self consistent and in agreement with the theoretical models of Kolb & Baraffe (2000), such a spectral type implies a secondary star mass, $M_2=0.10 M_{\odot}$. The same models also predict the spectral type of the secondary star as a function of orbital period. For an orbital period appropriate to V2301 Oph (113 min) the models predict a secondary of spectral type of M4.5 (Baraffe & Kolb 2000), which implies $M_2=0.15 M_{\odot}$ (Kolb & Baraffe 2000). For $M_2=0.10$ and 0.15 $M_{\odot}$ and $q=0.15$ (Reynolds et al 2005), this implies $M_1=0.67$ and 1.0 $M_{\odot}$ respectively.

For $M_1=1.0 M_{\odot}$, $M_2=0.15 M_{\odot}$ and $i=84^\circ$, we find that we can reproduce the observed duration of the standstill feature. Further, both accretion regions reappear simultaneously after eclipse (and hence no standstill is observed) if the accretion regions are located at ($90^\circ$, $10^\circ$) and ($60^\circ$, $45^\circ$) where the co-ordinates are $\beta, \xi$ (as defined by Cropper 1989). The shape of the accretion regions are expected to be more complex than simple circular regions, but we have found a solution which is self consistent and in agreement with the results of Reynolds et al (2005).

| Energy Band | X-ray Light Curve |
|-------------|-------------------|
| 0.15-0.5keV | 0.15-10keV        |
| 1-2keV      | 4-10keV           |

Figure 4. The X-ray light curves in 4 energy bands extracted from EPIC pn data folded on the quadratic ephemeris shown in §3.2. The time bins are 5 sec and the plot shows data from 2 eclipses. The ‘standstill’ which is visible in each light curve apart from the 0.15–0.5keV curve, has a duration of 26±4sec sec. The dashed line indicates 0.0 cts/s.

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For systems with high magnetic field strengths, strong cyclotron cooling would tend to suppress these QPO’s. Since V2301 Oph is believed to have the lowest magnetic field strength of any polar (Ferrario et al 1995) it is a good candidate for detecting QPOs.

We searched for QPOs in the X-ray light curve. We extracted events in the energy range 2–10keV (since these X-rays are expected to be emitted closer to the shock than soft X-rays) from various time intervals corresponding to both accretion regions. We searched for QPO’s using the event data and also in the light curves binned up into 0.1 sec bins in the frequency range 0.02-10 Hz using a Discrete Fourier Transform (DFT). We do not detect any evidence for peaks in the DFT above the noise level in this frequency range. We also searched for QPOs at softer X-rays (0.15–1.0keV) and again found no evidence for QPOs at these energies either.

To place constraints on the upper limit, we added a coherent signal of varying amplitude to the binned light curves. We found that we could not detect signals which had full amplitudes corresponding to 19–24% of the signal in the 2–10keV energy band. Steinman-Cameron & Imamura (1999) also found no evidence for QPO’s in either optical or X-ray data RXTE (2-60 keV). In X-rays they gave upper limits of 4.1–7.6% which is significantly lower than our limits. We believe that Steinman-Cameron & Imamura (1999) used data from all orbital phases in their analysis and they had a factor of ∼30 more counts compared to our 2–10keV band light curves.

The predicted modulation amplitude is sensitive to many parameters such as magnetic field strength, specific mass transfer rate, physical size and shape of the accretion region, (not to mention the energy band which is being used to measure the flux), so it difficult to compare the observed limits to predictions. However, these results suggest that even if there is an oscillation in the shock front it does not affect the observable X-ray flux - at energies which either XMM-Newton or RXTE are sensitive.

4 SPECTRA

4.1 RGS spectrum

V2301 Oph is bright enough in X-rays to us allow us to extract a phase averaged spectrum which has a moderate signal-to-noise ratio from the RGS detectors. We excluded data from a short time interval (550 sec) where the background was significantly higher compared to the rest of the observation.

We extracted first order source and background spectra from each detector using rgsproc. We co-added the spectra from both detectors using the procedure outlined by Page et al (2003) and then binned the spectrum so that it had a minimum of 40 counts per bin. We fitted the spectrum using the stratified accretion column model of Cropper et al (1999). Since the magnetic field strength of the white dwarf in V2301 Oph is low, we fixed the ratio of cooling due to cyclotron and bremsstrahlung emission at the shock front ($\epsilon_{\gamma}$) at a low value of 0.1. Further, we fixed the specific mass accretion rate, $\dot{m}$, at 1.0 g s$^{-1}$ cm$^{-2}$, the metal abundance at solar and $M_1=1.0 \ M_\odot$. The spectra and best fit ($\chi^2=1.01$, 158 dof) to this model are shown in Figure 5 (left).

The most prominent emission lines are those of the O VIII complex between 18.9–19.3Å (0.642–0.655 keV) and the O VII triplet between 21.6–22.1Å (0.561–0.574 keV). Less prominent emission is also seen from Mg XI (8.42 Å), Mg XII (9.2–9.3 Å) and Ne IX (or Fe XXII/XXIII). The accretion model of Cropper et al (1999) fits the O VIII emission at ∼21.0Å well, but not the O VII lines near 21.8 Å.

We then added 3 Gaussians to our model to fit the O VII triplet and fixed them at their expected rest energies (21.602, 21.804, 22.100 Å) and set their width to be zero. We found that we obtained a fit ($\chi^2=0.97$, 155 dof) which was better than the previous fit at a confidence of 97.4%. In principal we can use the fitted parameters of the Gaussian lines to the O VII complex to determine plasma diagnostic ratios. However, the errors to the fit were too large to be conclusive.

Ramsay et al (2004a) noted the presence of residuals in spectra extracted from EPIC spectra of polars at this energy and suggested that they may be due to the presence of an O VII emission line. Since V2301 Oph is one of the brightest polars in the XMM-Newton-MSSL polar survey this is the first time that we have been able to confirm the presence of this line in a spectrum taken using the RGS of a polar in our sample.

The accretion column model of Cropper et al (1999) sums up the contribution of optically-thin thermal plasma models (MEKAL) according to the prescription of Aizu (1973) and includes the effects of cyclotron cooling and the change in gravitational acceleration over the height of the shock. It therefore does not include emission due to photo-ionisation. We note that thermal plasma with very low temperatures (< 0.5keV) does emit O VII lines near 21.8 Å, but when the emission from hotter parts of the shock are included the line emission from O VII near 21.8 Å is negligible.

Comparing the RGS spectrum of V2301 Oph with other cataclysmic variables presented in Mukai et al (2003) the relative strength of emission lines due to O VII compared with the lines due to O VIII is similar to those systems which these authors identified as having spectra dominated by photo-ionisation. The fact that the accretion column model of Cropper et al (1999) fits the RGS spectrum well, with the exception of wavelengths centered on the O VII line, suggests that for polars their X-ray spectrum maybe best modelled with a contribution from photo-ionised line emission to the collisionally ionised plasma. This is to be expected since some fraction of the X-ray photons emitted in the post-shock flow will intercept the accretion stream resulting in emission of X-rays produced via photo-ionisation.

4.2 EPIC spectra

The light curves shown in the previous section suggest that there are two distinct accretion regions, one of which appears significantly softer than the other. Since the signal-to-noise of the EPIC data were much higher than the RGS data, we were able to extract phase resolved spectra from the EPIC data. We therefore initially extracted two spectra, one taken from the bright region ($\phi=0.05–0.2$) immediately after the deep eclipse (so that absorption effects were minimised) and one from the fainter pole when the softness ratio was significantly higher ($\phi=0.3–0.4$). We note the ‘bright’ accretion...
mined an upper limit on \( \dot{m} \) as done for our analysis of the RGS spectra. We initially piled up at the highest count rates, it is not surprisingly that parameters in Table 3. Since the EPIC pn data is slightly the bright accretion region. We show the fits and spectral §

\[ kT_e \sim 40\text{eV} \] (eg Ramsay et al 1994, Beuermann & Burwitz 1995 and references therein). Our initial fits to both the bright and faint regions showed that a soft blackbody component was not required to give good fits to the X-ray spectra. V2301 Oph therefore joins 7 other polars which have at least one accretion pole which does not show a soft X-ray component (Ramsay & Cropper 2004). Ramsay & Cropper (2004) proposed that these systems do have a soft X-ray component, but have a temperature low enough so that the blackbody is shifted to lower energies and therefore not seen using X-ray detectors which typically have low energy cut-offs near 0.1keV. We discuss this further in the next section.

In our analysis of the EPIC spectra we again used the accretion model of Cropper et al (1999) and fixed \( \epsilon_s=0.1 \) (as done for our analysis of the RGS spectra). We initially set \( \dot{m}=1.0 \text{ g s}^{-1} \text{ cm}^{-2} \). We included a neutral absorption model and a Gaussian emission line fixed at 0.571 keV (= 21.7Å) with zero width to include the O VII line due to photo-ionisation (§4.1).

We begin our discussion with the spectra extracted from the bright accretion region. We show the fits and spectral parameters in Table 3. Since the EPIC pn data is slightly piled up at the highest count rates, it is not surprisingly that the fits to the EPIC MOS data are marginally better than the EPIC pn data. Fixing the metal abundance at solar we find \( M_1=1.1-1.2 M_\odot \). Freeing the metal abundance gives masses which are lower by up to 0.1 \( M_\odot \).

From our analysis of the eclipse light curves we determined an upper limit on \( M_1 \) of 1.2 \( M_\odot \) (§3.3). Our derived masses assuming a specific mass accretion rate of 1.0 g s\(^{-1}\) cm\(^{-2}\) and solar abundance are therefore close to this upper limit. For a metal abundance less than solar the masses are more consistent with the results of the eclipse results. We have also examined the case of \( \dot{m}=0.1 \text{ g s}^{-1} \text{ cm}^{-2} \), performing the same analysis as before. For a range of metal abundance we find \( M_1=1.0-1.1 M_\odot \).

| Bright Pole | Faint Pole |
|-------------|------------|
| \( 31^{+1}_{-0.1} \) | \( 3.2^{+0.5}_{-0.3} \) |
| \( 74^{+3}_{-0.5} \) | \( 6.6^{+0.6}_{-0.6} \) |
| \( 20 \pm 1 \) | \( 1.8 \pm 0.1 \) |

Table 4. Using the fits to the EPIC MOS spectra, we show the observed flux in the 0.2-10keV energy band, the unabsorbed bolometric flux and the unabsorbed bolometric luminosity for the bright and faint poles assuming a distance of 150 pc (Silber et al 1994).

For the faint spectra we fixed \( M_1=1.05 M_\odot \) and \( \dot{m} \) at 1.0 and 0.1 g s\(^{-1}\) cm\(^{-2}\). We obtain good fits for both values of \( \dot{m} \) and show the fits in Table 3. This suggests that the derived parameters for the faint pole spectra are not sensitive to the specific mass transfer rate within the errors of the fit.

We show the observed flux, the unabsorbed flux and the luminosity (assuming a distance of 150 pc, Silber et al 1994) using the fits to the EPIC MOS data in Table 4. Assuming that the X-rays are optically thin we find the luminosity for the bright pole is \( 2\times10^{32} \text{ erg s}^{-1} \) and for the faint pole \( 1.8\times10^{31} \text{ erg s}^{-1} \). This compares with a mean value of \( 2.0\times10^{32} \text{ ergs s}^{-1} \) for the sample of polars in a high state observed using XMM-Newton (Ramsay & Cropper 2004). This suggests that the bright pole has an X-ray luminosity typical of polars. The fact that V2301 Oph shows the highest count rate of any of the poles in our sample makes it likely that it is one of the closest objects in our survey. To test this we searched the literature to obtain distances to all the polars included in the Ramsay & Cropper (2004) sample (we note that many are without even approximate limits to their distance). The only polar with a lower limit to its distance closer than 150 pc is GG Leo (Ramsay et al 2004) which has a lower limit of 100 pc (Burwitz et al 1998), and shows a peak count rate of \( \sim 3 \text{ ct/s} \) in the 0.15–10keV energy band in the EPIC pn.

Figure 5. The X-ray spectrum of V2301 Oph taken using the RGS (the data taken using the RGS1 and RGS2 detectors have been combined). In the left hand panel we show the fit using the model of Cropper et al (1999) and in the right hand panel the fit using the same model plus 3 Gaussian components near 21.8Å which were used to model the O VII line complex.
The parameters for the spectral fits to the bright and faint poles seen in V2301 Oph. We used a stratified accretion column model which includes the changing gravitational potential over the height of the accretion shock (Cropper et al 1999). We show the fit from data extracted from the EPIC pn detector and also the combined fit to data extracted from the EPIC MOS 1 and 2 detectors. In one fit we fixed the metal abundance at solar and in the other we allowed it to vary. We fixed the specific accretion rate at 1.0 and 0.1 g s\(^{-1}\) cm\(^{-2}\). Errors are given at the 90% confidence level.

### 5 THE ACCRETION REGION IN V2301 OPH

We found from our X-ray spectral fits that our accretion models predict \(M_1 = 1.1\)–1.2 \(M_\odot\) when we assumed \(\dot{m} = 1.0\) g s\(^{-1}\) cm\(^{-2}\) and \(M_1 = 1.0\)–1.1 \(M_\odot\) when we assumed \(\dot{m} = 0.1\) g s\(^{-1}\) cm\(^{-2}\). Our results from the eclipse profile showed that \(M_1 = 1.2\) \(M_\odot\) was an upper limit. The specific accretion rate cannot therefore not be much greater than 1.0 g s\(^{-1}\) cm\(^{-2}\).

What does this imply for the fractional area that accretion is occurring over? In §4.2 we found \(L_X = 2 \times 10^{32}\) erg s\(^{-1}\). If all the accretion energy is emitted as X-rays, this implies a mass transfer rate of \(8 \times 10^{14}\) g/s. For \(M_1 = 1.0 M_\odot\), this implies that accretion is occurring over a fraction, \(f\), of 0.002 and 0.0002 of the white dwarf surface for \(\dot{m} = 0.1\) and 1.0 g s\(^{-1}\) cm\(^{-2}\) respectively. (If a significant amount of accretion energy is emitted at other wavelengths then this fraction is a lower limit). The fraction implied for \(\dot{m} = 0.1\) g s\(^{-1}\) cm\(^{-2}\) is larger than normally seen in polars but similar to that found in intermediate polars (eg Rosen 1992, James et al 2002) - these binaries are accreting white dwarf whose magnetic field strength is not high enough to synchronise the spin of the white dwarf with the orbital period.

We noted earlier that many polars show a distinct soft X-ray component which is caused by re-processing of hard X-ray emitted in the post-shock flow by the photosphere of the white dwarf. V2301 Oph shows no evidence for this soft X-ray component and therefore joins 6 other polars with this feature. The temperature of the reprocessed component is proportional to \((M/f)^{1/4}\) where \(M\) is the total mass transfer rate (eg King & Lasota 1990). Therefore for large values of \(f\) and low values of \(M\) the effective temperature, \(T_{eff}\) will be lower. If this is sufficiently low this component will move out of the soft X-ray band and into the far UV.

Most intermediate polars do not show a distinct soft X-ray component. V2301 Oph which has the lowest magnetic field strength of any polar is consistent with this characteristic. Of the 7 systems which do not show a soft component 3 (BY Cam, RX J2115–58 and V1500 Cyg) are asynchronous polars (those polars in which the spin period of the accreting white dwarf and the binary orbital period differ by a few percent) which may imply that accretion flow is spread over a longer range of magnetic azimuth than normal. The specific accretion rate might therefore be too low over a significant percentage of the accretion region to produce a strong shock which will affect the presence and temperature of any reprocessed component.

### 6 ABSORPTION DIP

We extracted EPIC spectra taken from time intervals corresponding to the orbital phase during which there was the pre-eclipse absorption dip, and also time intervals just preceding this dip (which we call the ‘dip-free’ spectrum). The dip feature corresponds to the point in the binary orbital cycle where the accretion stream passes directly between the observer and the bright accretion region(s) on the accreting white dwarf for a wide range of viewing angles and magnetic field orientations.

We modelled the dip-free spectrum using the model described in §4.2. We find that the absorption column for the neutral absorber is \(4 \times 10^{20}\) cm\(^{-2}\) (consistent with that shown in Table 3). In modelling the pre-eclipse absorption dip spectrum we therefore fixed the absorption of this component at this value. As expected, the fits to the EPIC spectrum using this model was poor. We therefore added a second absorption model to account for stream absorption. For the latter we chose the \texttt{absori} and \texttt{pcf} models in \texttt{XSPEC}. The former

| Detector  | \(N_H\) (10\(^{20}\) cm\(^{-2}\)) | \(M_1\) (\(M_\odot\)) | \(Z\) (Solar) | \(\dot{m}\) g cm\(^{-2}\) s\(^{-1}\) | \(\chi^2\) (dof) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| EPIC pn   | 4.2±0.4         | 1.17±0.04       | 1.0             | 1.0             | 1.17 (286)      |
| EPIC MOS  | 4.8±0.7         | 1.19±0.03       | 1.0             | 1.0             | 1.05 (198)      |
| EPIC pn   | 4.5±0.7         | 1.14±0.03       | 0.50±0.22       | 1.0             | 1.12 (285)      |
| EPIC MOS  | 5.7±0.6         | 1.10±0.09       | 0.15±0.15       | 1.0             | 0.97 (197)      |
| EPIC pn   | 4.3±0.4         | 1.06±0.04       | 1.0             | 0.1             | 1.17 (286)      |
| EPIC MOS  | 4.9±0.8         | 1.09±0.05       | 1.0             | 0.1             | 1.03 (198)      |
| EPIC pn   | 4.3±0.4         | 1.06±0.04       | 0.5±0.2         | 0.1             | 1.17 (285)      |
| EPIC MOS  | 5.4±0.9         | 1.05±0.04       | 0.3±0.3         | 0.1             | 0.96 (197)      |

Table 3.
is a warm absorber which assumes an emission model which can be represented by a power law (here fixed at a slope of 1.4 which correctly fits the bright phase X-ray spectrum) and the latter is a partial covering model. Using the former of 1.4 which correctly fits the bright phase X-ray spectrum) can be represented by a power law (here fixed at a slope of 0.95, $\chi^2=0.84$, 447 dof). This absorption column density is similar to that found for RX J1002–19 but lower than in EV UMa (7 $\times$ 10$^{22}$ cm$^{-2}$, Ramsay & Cropper 2003).

7 CONCLUSIONS
V2301 Oph shows a unique standstill in its X-ray light curve. This allows us to place an upper limit of $M_1=1.2 M_\odot$ if we assume that the X-rays originate close to the white dwarf surface. Being the polar with the lowest magnetic field strength (7MG), V2301 Oph is the best target to detect QPO’s in the X-ray flux since higher field strengths are predicted to suppress oscillations. Our non-detection of QPO’s in X-rays suggest that either QPO’s are suppressed even for magnetic field strengths of 7MG or that they would only be detected at higher energies which are expected to be emitted closer to the accretion shock front. We find that V2301 Oph joins 6 other polars which do not show evidence for a distinct soft X-ray component. We believe that this is due to the fact that the temperature of the reprocessed component is low enough to be shifted out of the XMM-Newton pass band. We speculate that this could be due to the relatively high fractional area (derived from our fits to the EPIC spectra) that accretion is occurring on the white dwarf.

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