X-ray Spectroscopy of the IP PQ Gem

Cynthia H. James, Gavin Ramsay, Mark Cropper and Graziella Branduardi-Raymont

Mullard Space Science Laboratory, University College London, Holmbury St.Mary, Dorking, Surrey, RH5 6NT

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ABSTRACT

Using RXTE and ASCA data, we investigate the roles played by occultation and absorption in the X-ray spin pulse profile of the Intermediate Polar PQ Gem. From the X-ray light curves and phase-resolved spectroscopy, we find that the intensity variations are due to a combination of varying degrees of absorption and the accretion regions rotating behind the visible face of the white dwarf. These occultation and absorption effects are consistent with those expected from the accretion structures calculated from optical polarisation data. We can reproduce the changes in absorber covering fraction either from geometrical effects, or by considering that the material in the leading edge of the accretion curtain is more finely fragmented than in other parts of the curtain. We determine a white dwarf mass of $\sim 1.2$ using the RXTE data.

Key words: binaries: close - stars: individual: PQ Gem - stars: magnetic fields - novae, cataclysmic variables - X-rays: stars - accretion

1 INTRODUCTION

Magnetic cataclysmic variables (MCVs) can be split into two groups: those in which the magnetic field of the accreting white dwarf is strong enough ($\gtrsim 10^{11}$ G) to synchronise its spin period with that of the binary orbital period – the polars, and those with a magnetic field insufficiently strong to achieve this synchronisation – the intermediate polars (IPs). The MCV PQ Gem is unusual in that it exhibits characteristics of both groups: it shows a strong soft X-ray component ($kT \sim 50$ eV) (Duck et al. 1994), it is polarised in the optical/IR wave-bands (Potter et al. 1997; Piirona, Hakala & Coyne 1993) and has an estimated magnetic field strength of $8-21$ MG (Väth, Chanmugam & Frank 1996; Potter et al. 1997; Piirona et al. 1993) – all of which are characteristics of polars. On the other hand it shows a spin period of 833.4 sec (Mason 1997) and an orbital period of 5.19 hrs (Hellier, Ramseyer & Jablonski 1994) which are typical of IPs. PQ Gem can therefore be thought of as the first true “intermediate” polar (Rosen, Mittaz & Hakala 1993).

PQ Gem has been observed using several X-ray satellites (ROSAT, Ginga, ASCA & RXTE). The X-ray light curves show a prominent modulation on the spin period, in particular, a pronounced dip in the light curve which is thought to be due to an accretion stream obscuring the main emission region on the surface of the white dwarf. Mason (1997) made a study of the then available X-ray data to determine an accurate ephemeris for PQ Gem based on timings of the dip. However, a detailed study of the spectral information contained in the ASCA data was not undertaken.

This paper is primarily targeted at reaching a greater understanding of the interplay between the emission sites and absorption which produces the observed modulation of the X-ray light curves. This is achieved through analysis of the ASCA spectral data with supporting evidence from the hard X-ray RXTE light curves. The mass of the white dwarf is calculated from the RXTE spectral data using the stratified accretion column model of Cropper et al. (1999, subsequently CWRK). A fuller report is available in James (2001).

2 OBSERVATIONS AND DATA REDUCTION

2.1 ASCA

ASCA was launched in 1993 carrying two X-ray CCD cameras (SIS) and two imaging gas scintillation proportional counters (GIS), and operated until 2000 (Tanaka, Inoue & Holt 1994). The SIS detectors covered the energy range of 0.4 keV to 10 keV with an energy resolution of 2% at 5.9 keV. The GIS detectors had an energy range of 0.7 keV to 10 keV with energy resolution of 8% at 5.9 keV. Above 8 keV the GIS had a greater effective area than the SIS.

Details of the observations of PQ Gem are given in Table 1. The SIS detectors were configured to faint data mode 2-CCD (high bit rate) and 1-CCD (medium bit rate) clocking modes and the GIS detectors were configured to PH-mode. It is not possible to merge data from the different types of detector or from different SIS clocking modes without loss of information. Hence the end product of the data...
3 LIGHT CURVES

The quadratic spin ephemeris of Mason (1997) was used throughout the analysis of the light curves which were heliocentrically corrected.

3.1 Period Analysis

The variability in the RXTE and ASCA light curves was analysed using a standard discrete Fourier transform (DFT) code (Deeming 1975, Kurtz 1985). The equation, $z_0 = \ln[1 - (1 - p_0)^{1/N}]$, (Scargle 1982) was used to determine the power level, $z_0$, above which an amplitude peak would be spurious for a small fraction, $p_0$, of the time, where $N$ is the number of frequencies examined. A 90% confidence ($p_0 = 0.1$) was used to determine the signal-to-noise level above which the amplitude of a power peak was judged to be significant. The noise level of the periodogram was taken to be the mean of the amplitude spectrum after it had been prewhitened with frequencies found to be significant (Table 3). The error in each such frequency was taken to be the standard deviation, $\sigma$, from a least squares fitting.

The ASCA data showed three significant periods, 833.46s, 416.678s and 277.763s which are consistent with spin ephemeris of Mason (1997) and its first two harmonics. The RXTE data showed a significant period of 833.54s. The spin period (833 sec) is consistent with the spin down rate predicted by the ephemeris of Mason (1997). The complete results are given in Table 3 for those signals identified as significant at the 90 percent confidence level. The amplitude spectra, and window functions for the RXTE and ASCA are shown in Figure 3, along with the spectra prewhitened with the frequencies of the significant power peaks and the expected positions of the orbital, beat, spin frequencies and spin harmonics. The residual power peaks in the prewhitened RXTE periodogram are the 3rd harmonic of the spin period (> 68% confidence level) and the 1st and 2nd harmonics (<68% confidence level).

Using an orbital period of 5.19hrs (Hellier et al. 1994) a beat period at 14.54 min may be expected. However, there is no evidence for a significant amplitude at the frequencies corresponding to the orbital or beat periods in either the RXTE or the ASCA data (Figure 3). This indicates that the accreting material must go through a disc since all orbital information will then be lost.

3.2 ASCA light curves

Light curves of these data were first presented in Mason (1997) and also in James et al. (1998). They are presented here for completeness and comparison with those from RXTE. Light curves using data from the SIS0 detector for energy bands 0.7–1.0keV, 1.0–2.0keV and 2.0–4.0keV, 4.0–10.0keV and from the total bandpass (0.7–10.0keV) folded on spin period are shown on the left-hand side of Figure 3. The light curves were not folded on either the orbital or beat periods due to the lack of amplitude peaks found at these frequencies in the power spectrum of the ASCA data (3.1).

3.3 RXTE light curves

Light curves were extracted for the energy bands 2.0–4.0keV, 4.0–10.0keV, 8.0–25.0keV and from the total bandpass, 2.0–25keV, which were then folded on the spin period (right-hand side, Figure 3). The first two energy bands can be directly compared with similar plots using the ASCA data.

Table 1. Details of the ASCA observations and data used in the analysis for this paper.

| Date      | Instrument | Bit Rate | Integration Time (s) | Average cts/s |
|-----------|------------|----------|----------------------|---------------|
| 1994/11/04| SIS0       | high     | 26786                | 0.35          |
|           | SIS0       | medium   | 36910                | 0.38          |
|           | SIS1       | high     | 24732                | 0.29          |
|           | SIS1       | medium   | 34734                | 0.31          |
|           | GIS2       | high     | 27771                | 0.25          |

Table 2. Details of the RXTE PCA observations and data used in the analysis for this paper.

| Date       | Instrument | Integration Time (s) | Average cts/s |
|------------|------------|----------------------|---------------|
| 1997/01/27-30 | PCA       | 51216                | 13.9          |
Figure 1. Periodograms for the ASCA 0.5–10.0keV light curve (upper half) and RXTE 2.0–25.0keV light curve (lower half) of PQ Gem. In each half the top plot shows the window function, in the middle plot, the amplitude spectrum, and the bottom plot shows the spectrum prewhitened with the frequencies of the significant peaks. The vertical bars (from left to right) mark the position of the orbital, beat and spin (ω) frequencies plus the 1st, 2nd and 3rd harmonics of ω, respectively. The relevant details are given in §3.1 and Table 3.
3.4 Comparison between the ASCA and RXTE light curves

The RXTE PCA instrument overlaps the ASCA SIS instruments across the 2–10keV energy band. Hence this energy band from both instruments was used to compare the light curve modulation of the two observations (Figure 2). The light curves in these 2 bandpasses were found to be very similar, each with two maxima separated by a minimum at spin phase $\phi \sim 0.0$ (referred to as “the dip”, Mason et al. 1992) and a second minimum at $\phi \sim 0.6$. In the 4.0–10.0keV light curves the minima are relatively shallow in both the ASCA and the RXTE light curves, but the 2.0–4.0keV light curves show well defined “dips” at $\phi = 0.0$, with a broader minimum at $\phi \sim 0.6$. There is some evidence that the amplitude...
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Table 3. The details of the significant power peaks found from period analysis of ASCA SIS1 data and RXTE PCA data. The signal-to-noise ratio was taken as the amplitude of power peak to the mean of the prewhitened spectrum.

| Satellite | Instrument | Passband keV | Frequency mHz | Period s | S/N |
|-----------|------------|--------------|---------------|----------|-----|
| ASCA      | SIS1       | 0.7-10.0     | 1.19981(25)   | 833.46(17)| 8.0 |
|           |            |              | 2.39994(32)   | 416.678(56)| 7.1 |
|           |            |              | 3.60019(32)   | 277.763(25)| 6.6 |
| RXTE      | PCA        | 2.0-25.0     | 1.199703(81)  | 833.540(56)| 12.8|

of the variation in the RXTE folded light curve is less than that in the ASCA SIS data. The shape of “the dip” in the 2.0-4.0keV band is “V”-shaped in the RXTE compared to a more “U”-shaped in the ASCA light curve and its depth appears greater in the latter. This may be due to a higher level of absorption at the earlier epoch of the ASCA observation.

3.5 RXTE hardness ratios

Plots of the 8.0–25.0keV/2.0–8.0keV and 8.0–25.0keV/2.0–4.0keV hardness over the spin period are shown in Figure 3. The lower limit of the 8.0–25.0keV energy band was chosen so as to be well above the main absorption edges. A higher value of the ratio indicates those positions in the spin cycle which are more affected by absorption. These are consistent with the dip at φ = 0.0 being due to absorption.

4 SPECTRAL ANALYSIS

Because the energy resolution of the RXTE PCA (18% at 6.0keV) is much poorer than that of the ASCA SIS (2%), and does not extend to lower energies, the spectral analysis was restricted to the ASCA data. During the spectral analysis the medium and high bit rate SIS data from both instruments and the GIS data were linked through the models and fitted simultaneously.

4.1 Integrated Spectrum

The integrated spectrum was modelled using the MEKAL code for an optically thin emission model (Mewe, Kaastra & Liedahl 1995) for the hard X-ray spectrum and a blackbody model for the soft X-ray continuum. The temperature of the former was difficult to constrain, a problem which was similarly experienced by Duck et al. (1994) using Ginga data. Therefore the temperature was fixed at 20keV in line with the results from their analysis (we tried fixing the temperature at other values, but this did not have a significant effect on the results). The temperature of the blackbody component was not well constrained and therefore this spectral component was fixed at 55eV in line with that found with ROSAT data (Duck et al. 1994) due to its greater sensitivity to this spectral range. The fluorescent iron line at 6.4keV was modelled using a Gaussian component, the width of which was fixed at 0.05keV. A single homogeneous photo-electric absorber gave a poor fit (χ² = 2.0), therefore an inhomogeneous (partial covering) photoelectric absorber was added to the model. A good fit to the data was achieved in this way (χ² = 1.07). The values of those parameters allowed to vary during the fitting are given in Table 4 and the integrated spectra are plotted in Figure 4.

4.2 Phase-resolved Spectroscopy

Even though a good fit to the integrated spectrum was obtained, the results from the 8.0–25.0keV/2.0–8.0keV and 8.0–25.0keV/2.0–4.0keV hardness ratios using the RXTE PCA data indicate the possibility of variation in the absorption during the spin cycle (Figure 3, §3.5). These two results imply that variability in both the absorption and the normalisation of the hard X-rays over the spin cycle could be the cause of the observed modulation in the spin-folded light curves. In order to investigate this further we divided

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the spin period into 10 equal time bins and extracted spectra for each using data from both the SIS and GIS2 instruments. During all subsequent spectral fitting the medium and high bit rate data from both SIS and the GIS2 instruments were linked through the models and fitted simultaneously.

The reference model was derived from the medium and high bit rate data from the SIS1 and SIS0 instruments and the high bit rate data from the GIS2 instrument.

Table 4. Results from spectral analysis of the ASCA integrated spectrum of PQ Gem including the error range at 90% confidence level. The optically thin plasma and blackbody temperatures were fixed at 20keV and 55eV respectively. \( N_H \) (1) corresponds to the homogeneous absorber whereas \( N_H \) (2) applies to the inhomogeneous (partial covering) absorber; the flux is not corrected for absorption. The model was fitted simultaneously to the medium and high bit rate data from the SIS1 and SIS0 instruments and the high bit rate data from the GIS2 instrument.

| \( N_H \) (1) \( \times 10^{22} \text{ cm}^{-2} \) | \( N_H \) (2) (fraction) | BB norm: \( \times 10^{-3} \) | MEKAL norm: \( \times 10^{-2} \) | Gaussian norm: \( \times 10^{-5} \) | Flux(\text{observed}) \( \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \) | \( \chi^2 \) (dof) |
|--------|----------------|-------------|----------------|----------------|----------------|-------------|
| 0.12\( ^{+0.02}_{-0.01} \) | \( 8.3^{+0.9}_{-1.3} \) (0.53\( ^{+0.01}_{-0.02} \)) | 2.0\( ^{+2.3}_{-0.4} \) | 1.71\( ^{+0.05}_{-0.06} \) | 4.9\( ^{+1.3}_{-0.9} \) | 2.12 | 1.07 (1070) |

The resulting best fit parameter values from this analysis are shown in Table 4. The variations in the normalisation of the optically thin plasma, the column density and partial covering fraction are plotted in Figure 4 together with the folded light curve for the 0.5–10.0keV energy band of the ASCA data. It can be seen that the column density does not vary significantly over the whole spin cycle. The normalisation parameter of the hard X-ray component shows a maximum over 0.2 \( \leq \phi < 0.4 \), decreasing to a minimum at \( \phi = 0.7 \). The covering fraction of the partial absorber component shows a steady decline from its maximum value at \( \phi = 0.0 \) to a minimum value at \( \phi = 0.5 \). This pattern and phasing closely follows that of the RXTE 8.0–25.0keV/2.0–8.0keV hardness ratio, shown in Figure 3.

Relating this back to the main features of the modulation of the light curve shows that the maximum countrate (0.1 \( \leq \phi < 0.4 \)) is due to a combination of increasing normalisation coupled with a decreasing level of absorption. It would appear that an increase in the normalisation factor is probably the main cause of the second maximum (0.75 \( \leq \phi < 0.85 \)) of the light curve, but a contribution from a decrease in the covering fraction may also play a part. The secondary minimum (0.55 \( \leq \phi < 0.75 \)) is mainly due to a lower normalisation factor. Finally, “the dip” can be accounted for by the maximum value of the covering fraction, although, again, a contribution from a slight decrease in the normalisation factor cannot be ruled out.

5 MASS OF THE WHITE DWARF

5.1 Procedure

In recent years much work has been done in determining the shock temperature in magnetic CVs (e.g. Cropper, Ramsay & Wu 1998, Fujimoto & Ishia 1996). One of the main goals of this work has been to estimate the mass of the white dwarf since these two parameters are closely linked. To estimate the mass of the white dwarf in PQ Gem we use the emission model of Cropper et al. (1999) (CWRK) to fit data from the RXTE PCA detector (since it has an extended high energy range - the temperature of the hard X-ray component was poorly constrained using the ASCA data because of the 10keV upper limit). This model was developed to fit high quality X-ray spectra appropriate to the conditions found in the accretion sites of MCVs. It is a more complex model than the generalised optical thin plasma code we used for the phase-resolved spectroscopy.
The parameter, εs (the ratio of the cyclotron to bremsstrahlung cooling at the shock), was fixed at 0.5 which, from figure 1b of Wu, Channumag & Shaviv (1995) corresponds to a magnetic field strength of ~15MG (Pirola et al. 1993, Váth et al. 1996, Potter et al. 1997). We stratified the volume between the surface of the white dwarf and the shock front (Cropper et al. 1998) into 100 levels. The free parameters during the spectral fitting were the specific shock front into 100 levels. The free parameters during the spectral fitting were the specific shock front into 100 levels.

The height of the accretion column, the fractional area and the corresponding ˙φ < 0.5 which from figure 1b of Wu, Channumag & Shaviv (1995) corresponds to a magnetic field strength of ~15MG (Pirola et al. 1993, Váth et al. 1996, Potter et al. 1997). We stratified the volume between the surface of the white dwarf and the shock front (Cropper et al. 1998) into 100 levels. The free parameters during the spectral fitting were the specific shock front into 100 levels. The free parameters during the spectral fitting were the specific shock front into 100 levels.

The blackbody, bremsstrahlung normalisations and absorption include the error range at the 90% confidence level. The blackbody, Mekal and Gaussian normalisations are standard for the relevant xspec models. Also included are the χ²D and observed flux (i.e. not corrected for absorption) for the 10 phases.

Table 5. The variable parameter values from spin phase resolved spectral analysis over 10 phase bins. The reference model (0.4 ≤ φ < 0.5) was simultaneously fitted to the medium and high bit rate data from both of the SIS instruments and high bit rate data from the GIS2 instrument on the ASCA satellite. The normalisation and absorption parameters only were varied from those of the reference model. The blackbody, Mekal and Gaussian normalisations are standard for the relevant xspec models. Also included are the χ²D and observed flux (i.e. not corrected for absorption) for the 10 phases.

| Spin Phase | N_H (2) x 10^{22} cm^{-2} | Covering Fraction | BB Norm: 10^{-4} | MEKAL Norm: 10^{-2} | Gaussian Norm: 10^{-5} | Flux (observed) 2–10keV 10^{-11} erg cm^{-2} s^{-1} | χ²D (dof) |
|------------|-----------------------------|-------------------|-----------------|------------------|-------------------|---------------------------------------------|----------|
| 0.0-0.1    | 7.4^{+1.5}_{-1.5}           | 0.80^{+0.02}_{-0.02} | 0.48^{+1.03}_{-0.48} | 1.88^{+0.21}_{-0.21} | 7.96^{+2.94}_{-6.33} | 1.86                                          | 1.09 (149) |
| 0.1-0.2    | 8.6^{+2.4}_{-2.2}           | 0.70^{+0.03}_{-0.04} | 1.62^{+0.57}_{-1.60} | 2.10^{+0.26}_{-0.22} | 11.9^{+3.30}_{-5.66} | 2.17                                          | 1.00 (198) |
| 0.2-0.3    | 5.4^{+1.5}_{-1.3}           | 0.59^{+0.03}_{-0.03} | 1.24^{+0.51}_{-0.54} | 2.22^{+0.20}_{-0.16} | 12.7^{+3.20}_{-5.69} | 2.59                                          | 1.11 (248) |
| 0.3-0.4    | 5.7^{+1.2}_{-1.5}           | 0.55^{+0.03}_{-0.04} | 1.63^{+0.45}_{-0.64} | 2.21^{+0.21}_{-0.17} | 7.77^{+4.53}_{-4.21} | 2.55                                          | 0.91 (245) |
| 0.4-0.5    | 8.1^{+3.9}_{-2.7}           | 0.47^{+0.06}_{-0.05} | 1.14^{+0.55}_{-0.38} | 2.18^{+0.28}_{-0.20} | 8.00^{+5.30}_{-5.09} | 2.49                                          | 1.12 (253) |
| 0.5-0.6    | 3.8^{+1.0}_{-1.5}           | 0.43^{+0.04}_{-0.04} | 1.47^{+0.55}_{-0.43} | 1.79^{+0.17}_{-0.14} | 7.02^{+2.68}_{-5.94} | 2.23                                          | 1.08 (241) |
| 0.6-0.7    | 6.9^{+4.1}_{-2.6}           | 0.54^{+0.05}_{-0.06} | 0.58^{+0.48}_{-0.35} | 1.69^{+0.23}_{-0.17} | 11.7^{+3.30}_{-5.42} | 1.96                                          | 0.98 (202) |
| 0.7-0.8    | 4.0^{+1.9}_{-1.3}           | 0.52^{+0.03}_{-0.04} | 0.65^{+0.49}_{-0.36} | 1.61^{+0.13}_{-0.12} | 6.69^{+3.51}_{-3.89} | 1.96                                          | 0.99 (209) |
| 0.8-0.9    | 8.1^{+3.9}_{-2.7}           | 0.50^{+0.05}_{-0.05} | 0.52^{+0.47}_{-0.46} | 1.99^{+0.20}_{-0.18} | 4.21^{+3.98}_{-4.06} | 2.23                                          | 1.04 (231) |
| 0.9-0.0    | 4.8^{+1.5}_{-1.1}           | 0.58^{+0.03}_{-0.03} | 1.42^{+0.48}_{-0.55} | 1.87^{+0.16}_{-0.12} | 11.8^{+3.20}_{-5.24} | 2.2                                           | 0.95 (218) |

6 DISCUSSION

In section 5.2 we find that the spin phase modulation can be modelled well by a variation in the fractional covering fraction of a neutral absorber at low energies and in the normalisation at higher energies. Before we discuss this further, we briefly examine whether the modulation at both high and low energies can both be explained by a tall accretion shock.

In the case where the shock has significant vertical extent, the lower (cooler) part of the shock could be obscured by the limb of the white dwarf at certain spin phases. The light curves will then have a larger amplitude at low energies than at high energies (e.g. Allan, Hellier & Beardmore 1998). The height of the accretion column, H, can be estimated from the relationship

\[ H = 5.45 \times 10^8 M_{16}^{1/4} f_{-2} M_{WD}^{3/2} R_{WD}^{1/2} \]

(Frank, King & Raine 1991). Using the lower limit of the fractional area and the corresponding \(M\) derived in section 5.2 (cf Table 4) gives an upper bound of \(H = 5.4 \times 10^7\) cm or 0.14 \(R_{WD}\). However, the observational evidence suggests that PQ Gem has a significant magnetic field (\(\geq 10^8\)) which implies that the shock height will be lower than this (e.g. Cropper et al. 1999) due to cyclotron cooling. This suggests that this mechanism is not the cause of the variation. However, the accretion regions are likely to be sufficiently structured (e.g. Potter et al 1997) so that such a scenario cannot be excluded. On the other hand, because the spectral variations can be well modelled by a variation in covering fraction and...
6.1 Spin Pulse Modulation at Higher Energies

It is evident from an inspection of the 8–25 keV spin-phased RXTE light curve (Figure 2) and the spin-phased normalisation in the ASCA spectroscopy (Figure 5) that they are broadly similar. As this emission is expected to be at most weakly beamed, this indicates that the variation in intensity is caused by changes in visibility of the X-ray emitting region as the white dwarf rotates. The phase of maximum emission therefore corresponds to the phase of maximum visibility of the emitting region. There is possibly a slight phase shift between the two curves, with a clear peak at $\phi = 0.2$ in the RXTE light curve, and a more extended maximum around $0.2 < \phi < 0.4$ in the ASCA normalisation, but it is unclear given the uncertainties in the normalisations whether this is significant. Spin phases $0.2–0.4$ also correspond to the phases at which the accretion region in the upper hemisphere is seen most close to face on (Potter et al. 1997, figure 9). This suggests that this is principle cause of the spin pulse modulation at higher energies.

6.2 Spin Pulse Modulation at Lower Energies

At lower energies, the maximum in the covering fraction of the absorber at $\phi = 0.0$ is the major effect on the soft X-ray light curve, while the local increase at $\phi = 0.6$ combined with the decrease in normalisation at this phase to cause the second minimum ($\S$4.2). Potter et al. (1997) find that accretion occurs preferentially along field lines which thread the disc ahead of the accreting pole (their figure 12). Material accreting along these field lines can therefore be identified as the source of the absorption at phase 0.0. Similarly, at $\phi = 0.6$, in the absence of absorption by the disc (cf $\S$6.4), the local increase in covering fraction is likely to be caused by absorbing material along field lines which intersect the line of sight to the lower pole (Potter et al. 1997, figure 9). This suggests that this is principle cause of the spin pulse modulation at higher energies.

Figure 5. Results from spin phased-resolved spectroscopy of ASCA data. $0.4 < \phi < 0.5$ is the reference spin phase. The plots from the top are the spin folded light curve (included for clarity), the variation in the hard X-ray normalisation, the column density of the partial covering absorber and its covering fraction.

Figure 6. The effect fixing $\dot{m}$ to a range of values in the CWRK model during the spectral fitting. Details are given in $\S$6.4.

Table 6. Results from fitting the CWRK model to the RXTE PCA spectrum ($0.1 < \phi < 0.5$). Details of the spectral fitting process are given in $\S$5.

| Satellite | detector | angle $\phi$ | $N_{H,cold,1}(10^{22} \text{cm}^{-2})$ | $\dot{m} \text{ (g cm}^{-2}\text{s}^{-1})$ | $\chi^2 (\nu \text{ (dof)})$ | WD mass $M_\odot$ | unabsorbed flux (ergs cm$^{-2}$ s$^{-1}$) | luminosity $M_\odot$ | fractional area ($\text{ergs s}^{-1} \text{g}^{-1}$) |
|-----------|----------|-------------|-----------------------------------|-------------------------------|-----------------|-----------------|-----------------------------------|-----------------|-----------------------------------|
| RXTE PCA  | ~60      | 5.2         | 2.3                               | 9.5                           | 1.21 (1.16-1.28) | 0.89 (46)       | 6.3x10$^{-11}$                   | 1.2x10$^{32}$   | 3.0x10$^{15}$                     |

Table 7. The effect fixing $\dot{m}$ to a range of values in the CWRK model during the spectral fitting. Details are given in $\S$6.4.
the line of sight, while by $\phi = 0.4$, only field lines to the trailing part of the accretion region will do so. If the column density through accreting field lines is $\sim 5 \times 10^{22} \text{ cm}^2$, the observed variation in covering fraction in Figure 2 can be reproduced.

The accretion flow may be more finely fragmented along field lines feeding the leading edge of the accretion region. This would be expected because finely fragmented material is threaded by the magnetic field more easily than the larger denser inhomogeneities (e.g. Wickramasinghe 1988). From considerations of the packing fraction, the line of sight through more finely fragmented material is less likely to pass between gaps in the flow than in the case of the larger inhomogeneities. This effect would reproduce the high covering fraction at $\phi = 0.0$, and its subsequent decrease towards $\phi = 0.5$.

### 6.3 Accretion Model

The accretion scenario we are proposing fits neither the standard occultation model of King & Shaviv (1984) nor the accretion curtain model of Rosen, Mason & Córdova (1988). The orientation of the accretion region at spin phase maximum is as predicted by the occultation model, but with absorption effects modifying the light curve significantly. In this it is similar to the “weak field/fast rotator” model of Norton et al. (1999) with the symmetry of the accretion curtain about the magnetic axis modified by the leading field lines preferentially stripping material from the inner margin of the disc. The high (among IPs) magnetic field in PQ Gem and relatively high inclination and low dipole offset (Patterson et al. 1999) with the symmetry of the accretion curtain model of Rosen, Mason & Córdova (1988).

### 6.4 Occultation by the Accretion Disc?

Finally, we check whether the accretion disk can extend close enough to the white dwarf for it to have an affect on the X-ray light curves by obscuring the lower emission region.

Using the Ghosh & Lamb formulation (Li, Wickramasinghe & Rudiger 1996) the radius to the truncated inner edge of the accretion disc, $r_A$, is given by

$$ r_A = 0.52 \mu_{ WD}^{4/7} (2GM) ^{-1/7} M^{-2/7} $$

where $\mu_{ WD}$ is the magnetic moment of the white dwarf.

The magnetic moment can be estimated from the relationship $B = \mu/r^3$. Using the fits to the RXTE data and the model of CWRK we found a best fit to the white dwarf radius, $R_{ WD}$, of $3.8 \times 10^8 \text{ cm}$. Hence, with a magnetic field strength, $B_{ WD}$, of 15MG (Piiròla et al. 1993, Vähi et al. 1996, Potter et al. 1997), $\mu_{ WD}$ = $9.6 \times 10^{22}$ G cm$^3$. The accretion luminosity, $L_{ acc} = GM\dot{M}/R_{ WD}$

where $M$ is the mass of the white dwarf and $L_{ acc}$ is emitted mostly in the X-ray energy band, enables estimation of the accretion rate, $\dot{M}$.

6.5 The size of the Accretion Region

The unabsorbed spectral model from the analysis of the integrated spectrum ($\gtrsim$ 4.1) extrapolated for the energy range 0.001–100.0 keV gives the X-ray flux at $3.1 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ which, taking the distance to PQ Gem of 400 pc, gives a luminosity of $6.0 \times 10^{34} \text{ erg s}^{-1}$ and hence a mass transfer rate, $\dot{M}$, of $1.4 \times 10^{16} \text{ g s}^{-1}$. This is typical for IPs (Warner 1995). The resulting $r_A = 1.3 \times 10^{10}$ cm or $\sim 34 R_{ WD}$ may be too large given that an estimate of the distance to the first Lagrangian point is $\approx 200 R_{ WD}$ (Plavec & Kratochvíl 1964) (the main uncertainty in $r_A$ is in the magnetic moment $\mu_{ WD}$). Nevertheless it does indicate that with a system inclination of 60$^\circ$ (Potter et al. 1997), the line of sight to the white dwarf surface is likely to be clear of the accretion disc at all spin phases, and this is unlikely to contribute to the cause of the covering fraction variation.

6.6 The Mass of the White Dwarf

Previous determinations of the mass of the white dwarf in PQ Gem using an emission model fitted to Ginga data (Cropper et al. 1998, 1999) gave estimates $\geq 1.1 M_{\odot}$. In the case of the IP XY Ari, Ramsay et al. (1998) found that there was a good correspondence between the estimates given by this model and those from eclipse mapping. In our work it is found that the RXTE data gives estimates which are very much better constrained than those made with the ASCA SIS data. The estimate from our RXTE data of $M_{ WD} = 1.21 (1.16-1.28) M_{\odot}$ corresponds well to that of $1.21 (> 1.08) M_{\odot}$ obtained with Ginga data. Although this appears to be unusually high Ramsay (2000) found that the white dwarf in magnetic CVs were biased towards higher masses compared to isolated white dwarfs.

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