Pulse-phase-resolved spectroscopy of continuum and reflection in SAX J1808.4–3658

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ABSTRACT
We perform phase-resolved spectroscopy of the accreting millisecond pulsar, SAX J1808.4–3658, during the slow-decay phase of the 2002 outburst. Simple phenomenological fits to Rossi X-ray Timing Explorer Proportional Counter Array data reveal a pulsation in the iron line at the spin frequency of the neutron star. However, fitting more complex spectral models reveals a degeneracy between iron-line pulsations and changes in the underlying hotspot blackbody temperature with phase. By comparing with the variations in reflection continuum, which are much weaker than the iron-line variations, we infer that the iron line is not pulsed. The observed spectral variations can be explained by variations in blackbody temperature associated with rotational Doppler shifts at the neutron star surface. By allowing blackbody temperature to vary in this way, we also find a larger phase shift between the pulsations in the Comptonized and blackbody components than has been seen in previous work. The phase shift between the pulsation in the blackbody temperature and normalization is consistent with a simple model where the Doppler shift is maximized at the limb of the neutron star, ~90° prior to maximization of the hotspot projected area.

Key words: stars: neutron – X-rays: binaries – X-rays: individual: SAX J1808.4–3658.

1 INTRODUCTION
SAX J1808.4–3658 was the first accreting millisecond X-ray pulsar (AMXP) to be discovered (Wijnands & van der Klis 1998). Lying some 3.5 kpc distant (Galloway & Cumming 2006), the neutron star spins with a frequency of ~401 Hz and is thought to be orbiting a low-mass brown-dwarf companion (Bildsten & Chakrabarty 2001) with a 2.01-h orbital period (Chakrabarty & Morgan 1998). The established picture is that such AMXPs are recycled to millisecond periods from more slowly rotating neutron stars, due to the transfer of angular momentum from the accretion flow provided by the companion (Bhattacharya & van den Heuvel 1991). In this sense, the AMXPs bridge the gap between low-mass X-ray binaries (LMXBs) and rotation-powered millisecond pulsars.

The accretion flow in AMXPs differs from that in black hole X-ray binaries (BHXRBs) due to the stellar magnetic field and the solid neutron star surface. The magnetic field of SAX J1808.4–3658 is ~10⁸ G (Hartman et al. 2008), and this is sufficient to channel accreting material approaching within a few neutron star radii along field lines towards the magnetic poles. The funnelled gas passes through an accretion shock before falling on to the magnetic poles. X-ray observations of AMXPs made with the Rossi X-ray Timing Explorer (RXTE) and XMM–Newton have discovered distinct spectral components originating from these sources. The accretion disc and neutron star surface contribute to a soft component up to ~10 keV, and Comptonization in the shock region (most likely of seed photons from the impact hotspot) produces a harder component extending to ~100 keV (Gierliński, Done & Barret 2002). Recent XMM–Newton observations of SAX J1808.4–3658 have shown two distinct blackbodies at soft energies plus a hard component, interpreted as an accretion disc, a neutron star hotspot and an accretion shock (Patruno et al. 2009; Papitto et al. 2009).

In an analogous manner to reflection in BHXRBs (Fabian et al. 1989), it is thought that Comptonized photons reflect off the thin optically thick accretion disc producing a Compton reflection hump and fluorescent iron Kα line emission at ~6.4 keV (see Cackett et al. 2010, for a review of broadened iron lines in neutron star LMXBs). The shape of the line provides information about the distance of the line-forming region, since reflection occurring close to the compact object produces a characteristic asymmetric profile due to Doppler broadening and gravitational redshift. Observations of SAX J1808.4–3658 have revealed evidence suggestive of such a broadened iron line (Papitto et al. 2009; Cackett et al. 2009). Iron Kα lines are also of particular importance because they place a constraint on the magnetospheric radius. It is, as yet, unclear how the magnetic field of a magnetized star truncates the disc or what effect the star’s rotation has on the disc inner edge. The X-ray emission

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from AMXPs is pulsed due to misalignment of the spin and magnetic poles. As the hotspot and magnetically channelled accretion column rotate around the spin axis, the projected area and the magnitude of the Doppler shift change, causing emission to be pulsed at the spin frequency. It is therefore not unreasonable in this scenario to imagine that changes in the line shape and/or energy with phase might also occur. For instance, if the accretion column illuminates significantly different parts of the disc with phase, reflection occurring from approaching and receding parts of the disc should display a change in line energy with phase. Exploring the variation of the line properties with phase, as well as the phase-dependent correlation between the line equivalent width (EW) (or normalization) and the reflection hump, might be a valuable window on the formation of this spectral feature. The iron Kα feature in SAX J1808.4−3658 has been known about for many years (Gierliński et al. 2002), and we now know that this feature might be relativistically broadened (Papitto et al. 2009; Cackett et al. 2009). Therefore, it is of interest whether this feature is also pulsed at some level, which might be expected if the illuminating continuum is also pulsed as seen from the inner disc (which might be expected in certain geometries, e.g. where a part of the disc is shielded by the neutron star itself).

Using the correct orbital ephemeris and referencing the photon arrival times to the Solar system barycentre, it is possible to define an arbitrary phase-zero and ‘fold’ all of the incoming photons into phase bins representative of a full rotation of the neutron star. By examining the energy spectra of photons from individual phase bins, one can perform phase-resolved spectroscopy. A phase-resolved analysis was performed of the 1998 outburst (Gierliński et al. 2002), and the self-consistent continuum reflection and iron line were found to be consistent with having a constant value as a function of phase. In this work, we produce phase-resolved spectra of the best-sampled and best-studied 2002 outburst of SAX J1808.4−3658 as observed by RXTE over the ‘slow-decay’ of the outburst (Hartman et al. 2008) where pulse profiles are most stable, and we can investigate the phase-resolved spectrum with a high signal-to-noise ratio. We shall explore changes in the iron-line properties with phase and investigate the viability of the currently accepted picture of the broadened iron-line emission in AMXPs.

2 OBSERVATIONS AND DATA REDUCTION

We have concentrated on RXTE observations of SAX J1808.4−3658 from the slow-decay phase (MJD 52564–52574) of the 2002 outburst where the pulse profile is the most stable and the data are best sampled (in date order Obs ID 70080-01-01-02 to 70080-01-03-03 inclusive). The reader is referred to fig. 3 of Hartman et al. (2008) for a light curve of the outburst illustrating the data segment we used. For simplicity, only data taken with the E_125US_64M_0_1s event mode of the RXTE Proportional Counter Array (PCA) were used in this work. Although during these observations different PCA detectors were switched on, we have only analysed data from Proportional Counter Unit 2 (PCU2) which was always on, in order to ensure consistency. Gain and offset corrections, which attempt to match the energy scales in different PCU detectors, assign zero response in different channels of different PCUs (Jahoda et al. 1996). Combining different detectors involves weighting different detector responses, and this introduces unmodelled scatter into the data. In total, 64 event files were analysed with a total exposure of 167 ks, which provided sufficient signal-to-noise ratio for phase-resolved spectroscopy using 16 phase bins.

The photon arrival times in each event file were corrected to the Solar system barycentre with the tool foXYBARY. The photon phases were determined by using a high-order polynomial to ‘whiten’ the phase residuals and increase the signal-to-noise ratio of the pulsations. Additionally, the arrival time of photons was corrected for the orbital motion of the binary using a first-order approximation as outlined, for example, in Papitto et al. (2005). A folded pulse profile was created for each separate event file and fitted with a simple constant offset plus a sinusoid. During the slow-decay, phase profiles have been shown to be stable and nearly sinusoidal (Hartman et al. 2008; Ibragimov & Poutanen 2009). By fitting each event file with the best-fitting sinusoidal function, an offset could be determined for each event file to accurately align the different files in phase for subsequent summation. Custom code was written to select the photons from PCU2 only and produce separate FITS files containing events from each of the 16 different phase bins for each event file. The tool SEETRACT was then used to produce PHA spectra for each phase bin.

Background files were created using the tool PCBACKEST and extracted using SAETRACT over contemporaneous good time intervals created using the tool MAKTIME. The tool MATHPHA was used to sum PHA files from each respective phase bin and sum the background spectra. A weighted PCU2 response file was created (due to any variations in the response over time) from all observations using PCARSP and ADORMF. Care was taken to adjust the exposure of the phase-resolved spectra to reflect the fact that each spectrum only contained 1/16th of the total exposure. Phase-averaged PCU2 spectra were also obtained from the same observations.

The pre-processed High Energy X-ray Timing Experiment (HEXTE) cluster A spectra from the same observations were summed together to provide some constraints on the phase-averaged power-law spectral component at higher energies. Throughout this work, spectral fitting was performed using XSPEC version 12.5.1 (Arnaud 1996) with a 0.5 per cent systematic error for PCA and HEXTE data during fitting. It should be noted that the PCU2 data have zero response in channel 10, but these counts are redistributed to other channels, hence the gap in the data in Fig. 2.

3 ANALYSIS AND RESULTS

3.1 Phase-averaged spectrum

Phase-averaged spectra of SAX J1808.4−3658 from the slow-decay phase of the 2002 outburst have been fitted before (Ibragimov & Poutanen 2009). It is therefore known that a simple power-law fit shows residuals that are consistent with Compton reflection and blackbody hotspot emission. In both the 1998 and 2002 outbursts, thermal Comptonization models have typically shown photon indices of ~1.8 with blackbody temperatures of around 0.7 keV and hotspot areas in the range of 20–110 km^2 (Gierliński et al. 2002; Poutanen & Gierliński 2003; Ibragimov & Poutanen 2009).

As well as fitting PCA data over 3.0–25.0 keV, the HEXTE spectra are also fitted simultaneously over the range of 15.0–150 keV to constrain the power-law continuum and cut-off energy. The continuum was best modelled using the thermal Comptonization model nthcomp (Zycki, Done & Smith 1999) and reflection was modelled using peXriv (Magdziarz & Zdziarski 1995) and GAUSSIAN components convolved with eddblur. Only the reflection component of the peXriv model was included. A thermal Comptonization model is chosen since the hot electrons in the accretion shock are thought to Compton up-scatter the seed photons from the hotspot, whilst the blurred Gaussian is chosen to model the iron-line feature. All
parameters were tied between the two instruments apart from a normalizing constant to allow for a calibration offset. The hotspot emission is modelled using a BROADRAD component. The BROADRAD model is a single temperature blackbody spectrum parametrized by the temperature and the normalization $R_{22}^2 \times D_{10}^2$, where $R_{22}$ is the source radius in km and $D_{10}$ is the distance to the source in units of 10 kpc. The NTHCOMP model is parametrized by the asymptotic power-law photon index, the electron temperature, the seed photon temperature and the normalization (the photon flux defined at 1 keV in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$). The PEXRIV model describes an exponentially cut-off power-law spectrum reflected from ionized material and is parametrized by the power-law photon index, the power-law cut-off energy, the disc temperature, the disc ionization parameter (Done et al. 1992), the normalization (photon flux at 1 keV) of the power law only (without reflection) and a dimensionless reflection scaling factor. RDBLUR is a convolution model taking account of the blurring due to relativistic effects from an accretion disc around a non-rotating black hole and is parametrized by the power-law index of emissivity, the disc inner radius, the disc outer radius and the inclination. Full parameters of the fit are shown in Table 1 and the unfolded spectrum is included in Fig. 1. The spectral fits reflect the average parameters over the 167-ks of data we analysed from the slow-decay phase of the outburst. The parameters of this ‘average’ fit are consistent with previous work, though it should be noted that as the mass accretion rate drops throughout the outburst, the disc inner edge likely recedes (Ibragimov & Poutanen 2009), causing changes in the fit parameters. The fits were insensitive to $\xi$, the ionization parameter, and the disc temperature, so these were frozen at values of 100 erg cm s$^{-1}$ and 10$^4$ K, respectively. The low value of $\xi$ is consistent with the line energy which was constrained to lie between 6.4 and 6.9 keV and pegged at the lower limit during fitting. In order to avoid the PEXRIV power-law cut-off energy becoming unphysical, this parameter was constrained to be equal to three times the value of the electron temperature. Freeing the seed photon temperature for Comptonization from the blackbody temperature had no statistically significant effect, consistent with the notion that the seed photons for Comptonization come from the hotspot emission. It should also be noted that the PEXRIV normalization and reflection fraction are degenerate parameters in these fits, hence the large absolute values of reflection fraction quoted in Table 1. The relatively poor $\chi^2$ value of the model quoted in Table 1 is due to the higher energy HEXTE data. Removing the HEXTE data and fitting only PCA data result in a $\chi^2$/degree of freedom (d.o.f.) of 16.56/18, but it was considered important to include the HEXTE data during fitting to better model the electron cut-off and thermal Comptonization continuum. Grouping the HEXTE data into bins of four channels each in this fit improves the $\chi^2$/d.o.f. to 38.44/28, a perfectly acceptable fit given the low number of d.o.f. Previous pulse-profile modelling (Poutanen & Gierliński 2003) has derived a lower limit of 65$^\circ$ for the inclination of this source, but since no eclipses or absorption dips are seen, a value of 60$^\circ$ is assumed throughout this work consistent with previous analysis (Gierliński et al. 2002; Ibragimov & Poutanen 2009). Any difference in inclination only introduced a systematic shift in the normalization of spectral components and therefore did not effect the relative phases of any pulsations.

Table 1. Best-fitting parameters for the phase-averaged CONSPHABS[NTHCOMP+ BROADRAD+RDBLUR][PEXRIV+GAUSSIAN] model used in Section 3.1.

| Parameter | Value |
|-----------|-------|
| BBTL (keV) | 0.676$^{+0.02}_{-0.01}$ |
| BBnorm | 130.89$^{+10.12}_{-12.87}$ |
| $\Gamma$ | 1.96$^{+0.03}_{-0.01}$ |
| NTHCOMP kT$_e$ (keV) | 45.53$^{+16.08}_{-8.10}$ |
| NTHCOMPnorm | 0.051$^{+0.004}_{-0.04}$ |
| foldE (keV) | 136.59$^{+22.24}_{-24.30}$ |
| PEXRIVnorm | 0.034(Frozen) |
| PEXRIVrefl | -3.96$^{+0.93}_{-0.69}$ |
| PEXRIV$\xi$ | 100(Frozen) |
| HEXTEconst | 0.88$^{+0.01}_{-0.01}$ |
| $R_{22}$ (RG) | 18.41$^{+29.15}_{-12.41}$ |
| Emissivity | -3.30$^{+7.1}_{-6.7}$ |
| Fe line E (keV) | 6.40$^{+0.08}_{-0.08}$ |
| Fe linewidth (keV) | 0.01(Frozen) |
| Fe norm (10$^{-4}$) | 6.11$^{+2.04}_{-1.04}$ |
| $\chi^2$/d.o.f. | 97.18/62 |

Note. Inclination was fixed at 60$^\circ$, $R_{22}$ fixed at 1000RG, $n_H$ fixed at 0.113 $\times$ 10$^{22}$ and solar abundances assumed. Upper/lower error limits labelled with an asterisk show that the fit parameters were pegged, at times indicating that the fit was not particularly sensitive to this parameter.
3.2 Phase-resolved energy spectra

3.2.1 Evidence for a varying iron-line EW with phase

A simple phenomenological fit was performed to the 16-bin phase-resolved data consisting of a **PHABS**(POW+BBDYRAD) model. The absorption was fixed at $0.113 \times 10^{22}$ cm$^{-2}$ as in Ibrahimov & Poutanen (2009) (obtained from the HEASAR tool *nh*) and the fit performed over the region of 3.0–25.0 keV whilst ignoring the iron-line region of 5.5–10.0 keV. Component normalizations were allowed to be free for each of the 16 different spectra. Having fitted a model excluding the data in the iron-line region, one can plot the data-to-model residuals by then including the data in this region as shown in Fig. 2. The plot of the residuals demonstrates a broad iron-line feature and hints at a changing iron-line EW with phase.

In the following sections, we shall explore different models to explain this apparent pulsation of the iron line with phase.

3.2.2 Phenomenological fits

A fit was performed with the model **PHABS**(CUT-OFFPL+BBDYRAD+DISKLINE), using the 16 phase-resolved spectra over 3.0–25.0 keV and the phase-averaged *HEXTE* spectrum over 15.0–150.0 keV. The iron-line energy was constrained to lie within 6.4 and 6.9 keV and the inclination fixed at 60° as in Gierliński et al. (2002) and Ibrahimov & Poutanen (2009). With the cut-off power-law and blackbody normalizations free to vary between phase bins (untied), and the DISKLINE normalization constrained to its best-fitting value across all phase bins (tied), the fit gave a $\chi^2$/d.o.f. of 756.52/467. The best-fitting DISKLINE $R_{\infty}$ was 11.9 $R_{\odot}$ and the low value (1.63) of power-law photon index (compared to the phase-averaged fits) points to some degeneracy between the power-law and blackbody contributions at soft energies in this simple fit. Untying the DISKLINE normalization between phase bins improved the $\chi^2$/d.o.f. to 694.46/451, and the spectral components demonstrate the pulsations shown in Fig. 3. Untying the DISKLINE normalization simply allows the flux from the line to change with phase, rather than assuming that the flux is constant as a function of phase. If the blackbody temperature is untied between phase bins instead of the DISKLINE normalization, the $\chi^2$/d.o.f. improves to 691.38/451 and the spectral components this time pulsate as shown in Fig. 4. Untying the blackbody temperature produces an $\sim 80°$ phase shift in the pulsation of the blackbody normalization compared to Fig. 3, suggesting that there is some offset between the Doppler shift of blackbody photons (that affects the temperature measured by an observer at infinity and is dependent on the maximum line-of-sight velocity) and the projected area of the hotspot which dominates the blackbody normalization. It is also interesting to note that the DISKLINE normalization and $kT$ are in phase in Figs 3 and 4, respectively. Again, it should be pointed out that the poor $\chi^2$/d.o.f. is due to the higher energy *HEXTE* data used to constrain the parameters in this fit. If a fit is performed excluding the *HEXTE* data (fixing the now unconstrained high-energy cut-off to the phase-averaged values), the $\chi^2$/d.o.f. improves to 473.58/407. Although the fits obtained with this simple phenomenological model are formally unacceptable, they do provide some physical insight into the nature of the pulsations in this source which are discussed below. The detailed reflection models explored in Section 3.2.3 produce much more acceptable values of reduced $\chi^2$.

This preliminary analysis leads to two explanations for the spectral pulsation, which are equally likely on statistical grounds alone.

![Figure 2](https://example.com/fig2.png)  
**Figure 2.** Data to **PHABS**(POW+BBDYRAD) model residuals showing a broad excess in the iron-line region. For clarity, only three of the 16 phase bins are shown here. The slight soft excess is most likely due to the Wien tail of accretion disc emission. The zero-point from PCU channel 10 has been removed from this plot as discussed in the last paragraph of Section 2.

![Figure 3](https://example.com/fig3.png)  
**Figure 3.** Phenomenological fit demonstrating the pulsation in the **DISKLINE** normalization with phase. The blackbody temperature was tied between phase bins in this fit. The approximate peak-to-peak change in the line normalization was 42 per cent, in the blackbody normalization 20 per cent and in the power-law normalization 11 per cent.

![Figure 4](https://example.com/fig4.png)  
**Figure 4.** Phenomenological fit demonstrating the pulsation in the blackbody temperature when **DISKLINE** normalization is tied between phase bins. The approximate peak-to-peak change in the blackbody temperature was 5 per cent, in the blackbody normalization 28 per cent and in the power-law normalization 11 per cent.
In the first case, the line normalization is pulsating due to solid angle changes of the line-emitting region and in the second case the line normalization itself is constant, but the changing spectral shape of the blackbody component (governed by temperature changes, possibly due to Doppler effects) introduces a modulation at the spin frequency. It is important to point out here the physical situation that these alternative models are describing. In the first case, which invokes a varying line normalization, the visible area of line emission changes with phase. This could, for instance, be due to the neutron star self-shielding the line emission from the disc as the system rotates, as shown in Fig. 5, or due to solid angle changes of the emitting area with phase. In the second scenario, where the line emission is constant with phase, the alignment of the spin and magnetic poles is such that the illumination of the disc by the accretion shock is more or less constant with phase as depicted in Fig. 6. The amount of observed iron-line emission is therefore fairly constant with phase, and the modulation can be explained solely in terms of the spectral changes in the blackbody component occurring in the same energy channels as the iron line.

3.2.3 Fits with reflection models

Having established these two alternative scenarios using the phenomenological fits, the same physically motivated reflection model described in the phase-averaged fits was fitted to the phase-resolved spectra (and HEXTE spectra). In the first fit, the normalizations of the BBODYRAD, NTHCOMP, PEXRIV and GAUSSIAN components were untied between phase bins, whereas the blackbody temperature and seed photon temperature were tied between phase bins (and tied to each other). Throughout these phase-resolved fits, all parameters constrained to not vary with phase remained very close to the phase-averaged values quoted in Table 1. The $\chi^2$/d.o.f. for this fit was 455.0/435, and the pulsation of the spectral components with phase can be seen in Fig. 7.

It is clear from Fig. 7 that, in this model, the Gaussian (iron-line) normalization is systematically varying with phase, whilst the reflection normalization shows no clear evidence of doing so. We jointly fitted both the GAUSSIAN and PEXRIV normalizations shown in Fig. 7 with a simple constant offset plus a sinusoid, which forced the fractional amplitude and phase of the normalization variations to be the same. The fit was poor but was significantly improved by untying the phase ($\Delta \chi^2 = 3.23$ for one additional free parameter) and amplitudes ($\Delta \chi^2 = 4.69$ for one additional free parameter). The likelihood of an observed improvement by chance was 0.003 and $3.7 \times 10^{-6}$ for untying phase and then fractional amplitude, respectively. The fractional amplitude of variation in the PEXRIV normalization was close to zero, i.e. consistent with a constant PEXRIV reflection component. This inconsistency in the reflection components is the most compelling evidence that the ‘iron-line pulsation’ is actually no more than a change in the underlying blackbody spectral shape with phase. The reflection and iron-line normalization should be strongly correlated in amplitude and in phase with one another because they both emerge as a consequence of hard X-ray irradiation of the disc. In fact, Fig. 7 demonstrates no discernible pulsation in the PEXRIV component at all.

Untying the blackbody temperature between phase bins in this fit did not significantly improve the fit.

A second fit was performed to the phase-resolved spectra using the same model described in the phase-averaged fits, but this
time constraining the reflection and line normalizations to be constant with phase. The $\chi^2$/d.o.f. of this fit was 492.46/467. Allowing the blackbody temperature to also vary with phase (it was still assumed that the blackbody temperature and seed photon temperature for Comptonization were identical) improved the $\chi^2$/d.o.f. to 464.07/451 with an $f$-test probability of 0.039. The variations with phase are shown in Fig. 8. Again, as with the earlier phenomenological fits, the blackbody normalization is shifted along in phase when the blackbody/seed photon temperature is a free parameter.

Fig. 9 shows 99.9 per cent confidence contours for three phase bins (1, 6 and 11) of blackbody temperature against blackbody normalization and demonstrates that the temperature and normalization are correlated. However, the fact that the 99.9 per cent contours do not overlap significantly in temperature for a given normalization (and vice versa) and there is no anticorrelation in the pulsations of these components in Fig. 8 suggests that the pulsation in these components might be real.

Untying the seed photon temperature for thermal Comptonization and the blackbody temperature had no significant effect on the spectral fits. There is no concrete statistical evidence to favour blackbody temperature variations over varying reflection, but there is a good physical reason to do so as outlined above. The best fit arises by invoking a changing blackbody temperature with phase and, although the error bars are large, the amplitude and shape of reflection variations do not match the line variations seen in Fig. 7. In the next section, we will show that the observed variations can be explained quite simply in terms of the Doppler shifts (to produce the observed hotspot temperature variation) and solid angle changes (to produce the normalization variation) which are expected for this system.

Table 2 shows the fractional rms values for the different model components of each model described above.

### Table 2. Fractional rms values for different model components.

| Component      | Fig. 3 | Fig. 4 | Fig. 7 | Fig. 8 |
|---------------|--------|--------|--------|--------|
| DISKLINE      | 0.157  | n/a    | n/a    | n/a    |
| BBODYnorm     | 0.072  | 0.10   | 0.083  | 0.046  |
| Power law     | 0.039  | 0.039  | n/a    | n/a    |
| $kT$          | n/a    | 0.018  | n/a    | 0.015  |
| NTHCOMPnorm   | n/a    | n/a    | 0.044  | 0.030  |
| PEXRIVnorm    | n/a    | n/a    | 0.020  | n/a    |
| GAUSSnorm     | n/a    | n/a    | 0.155  | n/a    |

Note. Fractional rms values are obtained from the best-fitting constant offset plus sinusoid model. The quoted value for the PEXRIV normalization is an upper limit.

### 4 DISCUSSION

The rms values shown in Table 2 for the physically motivated reflection model invoking blackbody temperature variations (Fig. 8) suggest a larger variation in the blackbody component than the Comptonized component. As shown in Fig. 10, this is most likely due to blackbody emission arising from a flatter, more horizontally extended ‘pancake’-type region compared to the Comptonized emission from the accretion shock which could extend vertically from the neutron star surface. As the star rotates, the projected area of the blackbody region changes more than the accretion shock region, leading to a greater amplitude of variation. The fractional variation from the Comptonized emission might also be reduced if the accretion column is relatively optically thin (which mitigates the effect of solid angle variation) or if there exists a second, constant Comptonizing region, e.g. an extended corona. The pulsation in the Comptonized component is significantly out of phase with the
blackbody component, as seen in previous work (Gierliński et al. 2002; Ibragimov & Poutanen 2009). However, the phase shift of ~170° between these components in Fig. 8 (when $kT$ is a free parameter) is much larger than in previous work where the shift was ~50° (Gierliński et al. 2002) and ~70° (Ibragimov & Poutanen 2009) with $kT$ being fixed. By fixing the blackbody temperature, the offset between the blackbody and Comptonized component is found to be ~50°, consistent with Gierliński et al. (2002). It would therefore appear that some of the role of changing normalization is subsumed by the changing $kT$, shifting the variations in blackbody normalization to later phases. It is perhaps surprising how sensitive the phase shift of the blackbody component pulsations are to the choice of model used. If the accretion column is optically thick and vertically elongated above the neutron star surface (as argued above), then the solid angle of the column could be maximized when it points away from the observer. This would coincide with the minimum projected hotspot area and can therefore explain the ~180° phase shift between the blackbody and Comptonized components.

For a 15-km neutron star, the Doppler shift $\Delta E/E = 2\pi c R v/c$ produces a large shift at the equator (e.g. around 13° per cent at a rotation frequency of 401 Hz). For an accretion shock aligned at 10° to the rotation axis, the upper limit obtained by Ibragimov & Poutanen (2009), $R$ is reduced from 15 km at the equator to just 2.6 km and the Doppler shift is reduced to just 2 per cent. If we discount the possibility of pulsed iron-line variations (as implied by the much weaker variations in the reflection continuum), the phase-resolved fits suggest that some of the pulsed variation in the spectral shape can be explained by a varying Doppler shift of the blackbody photons underlying the iron line. If we associate the blackbody temperature change with a Doppler shift, Fig. 8 demonstrates a peak-to-peak change in temperature of approximately 0.035 keV which in this source, assuming an inclination of 60°, translates to a radius of rotation of 3.5 km, consistent with the arguments of Poutanen & Gierliński (2003). This shift is consistent with a hotspot aligned at approximately 13.5° (20°) to the rotation axis, for a 15-km (10-km) radius neutron star. The fact that the shock makes a small angle with the rotation axis of the neutron star implies that the whole inner disc is illuminated more or less evenly, i.e. there is no preferential illumination of different parts of the disc with different line-of-sight velocities which would lead to a change in the iron-line shape with phase.

A phase shift measured as ~80° can be seen in Fig. 8 between the pulsation in the blackbody temperature (driven by Doppler variations) and the blackbody normalization (driven by projected area effects). As discussed in Gierliński et al. (2002), this is consistent with a geometry where Doppler variations are strongest when the hotspot is at the limb of the star, and projected area effects are strongest ~90° later when the solid angle of the hotspot is maximized. Clearly, this picture is only approximate, since we do not take account of effects such as light-bending (e.g. Ibragimov & Poutanen 2009).

Our fits to these data are consistent with the idea that the iron-line shape and normalization remain constant with phase, suggesting a geometry where the illumination of the disc by the accretion shock is fairly constant. By assuming that the only variable components are the normalizations of the blackbody and Comptonized components (Gierliński et al. 2002; Ibragimov & Poutanen 2009), one can detect an apparent pulsation in the residual iron-line component. However, any apparent change in the iron-line normalization with phase can be explained by taking into account the Doppler boosting of the underlying blackbody continuum. The constancy of the iron line is not really surprising, because for the small offset of the accretion column from the rotation axis that is envisaged here, the disc will not see much variation in solid angle of the accretion-shock region, and variations in Doppler beaming of the accretion-shock emission towards the disc will be small. The presence of a constant power-law continuum component from a corona would also serve to reduce the variability of the iron-line emission.

5 CONCLUSIONS

Phase-resolved spectroscopy of the 2002 outburst of the AMXP SAX J1808.4—3658 as observed by RXTE reveals no convincing evidence for pulsations in the iron line or changes of any line properties with phase. By allowing the blackbody spectral shape to change (i.e. freeing the blackbody temperature during fitting), one can allow for variable Doppler boosting of the underlying blackbody continuum, which introduces a larger phase shift between the Comptonized component normalization and the blackbody normalization than has been seen in previous work. The phase shift between the blackbody normalization and the blackbody temperature is approximately consistent with the expected 90° offset between the maximum projected area and maximum Doppler shifts. The fraction of the disc illuminated by the Comptonizing region appears to be roughly constant with the rotational phase.

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