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Identifying a new intermediate polar using *XMM–Newton* and *INTEGRAL*

Matthew J. Middleton,[1★] Edward M. Cackett,[2] Craig Shaw,[1] Gavin Ramsay,[3] Timothy P. Roberts[1] and Peter J. Wheatley[4]

[1] *Department of Physics, University of Durham, South Road, Durham DH1 3LE*
[2] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA*
[3] *Armagh Observatory, College Hill, Armagh BT61 9DG*
[4] *Department of Physics, University of Warwick, Coventry CV4 7AL*

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ABSTRACT

The bright X-ray source 2XMMi J180438.7−145647 is fortunate to have long baseline observations in *INTEGRAL* that complement observations taken by other missions. Optical spectroscopy of this object has suggested a distance of ∼7 kpc and an identification with a low-mass X-ray binary. We instead use the X-ray data from 0.3 to 40 keV to identify the source as a bright intermediate polar (IP) with an estimate for the white dwarf mass of $\sim 0.60\,M_{\odot}$. This identification is supported by the presence of an iron triplet, the component lines of which are some of the strongest seen in IPs, and the signature of the spin period of the white dwarf at ∼24 min. We note that the lack of broad-band variability may suggest that this object is a stream-fed IP, similar in many respects to the well-studied IP, V2400 Oph. Phase binning has allowed us to create spectra corresponding to the peaks and troughs of the light curve from which we determine that the spectra appear harder in the troughs, consistent with the behaviour of other IPs binned on their spin periods. This work strongly suggests a misidentification in the optical due to the presence of large columns of enshrouding material. We instead propose a distance to the source of <2.5 kpc to be consistent with the luminosities of other IPs in the dim, hard state. The considerable flux of the source together with the strength of the iron lines may, in future, allow the source to be used to diagnose the properties of the shock-heated plasma and the reflected component of the emission.

Key words: accretion, accretion discs – novae, cataclysmic variables – X-rays: binaries.

1 INTRODUCTION

Cataclysmic variables (CVs) populate the central-to-faint section of the Galactic X-ray luminosity function (10^{31}–10^{34} erg s^{-1}; see Sazonov et al. 2006) and may provide a substantial percentage of the hard X-ray emission seen in the Galactic ridge (Revnivtsev et al. 2009a). In such systems, accretion from a low-mass donor star (Cowley et al. 1998, but see also Orio et al. 2010) on to the white dwarf (WD) may occur via either an accretion disc (Shakura & Sunyaev 1973) or via columns of material following the WD's magnetic field lines and impacting the poles. The latter system is dubbed a polar or intermediate polar (IP) system dependent upon the magnetic field strength, and the emission is typified by cooling of shock-heated gas near the WD surface (see Cropper 1990, for a review of polars) and imprinted absorption and emission features.

Such systems may be seen to enter a nova outburst state where the material builds up on the surface of the WD leading to thermonuclear burning (Pietsch et al. 2005). The observational result of a nova is a supersoft source (SSS), but following this they enter a persistent and much dimmer, harder state (although the long-term behaviour can also include brighter episodes due to dwarf novae from disc instabilities; e.g. Idan et al. 2010). The highest luminosity of this low state has been attributed to GK Persei ($\sim 1.1 \times 10^{34}$ erg s^{-1} in a 2006 outburst) although there is still uncertainty in its distance [∼340 pc (Warner 1987) to 525 pc (Duerbeck 1981)], and this is potentially exceeded by a CV in M3 (1E1339 with a luminosity of $\sim 1.4 \times 10^{34}$ erg s^{-1} – Stacey et al. 2011).

A further feature of such objects is the presence of periodicity in the X-ray and optical light curves, indicating either the orbital periodeq of the secondary (from the optical emission) ranging from ∼1.4 to 50 h (Crampton, Fisher & Cowley 1986; Hilton et al. 2009) or the spin period of the WD, taking values between ∼30 s (de Jager et al. 1994) and ∼4000 s (Mauche et al. 2009). These presence and behaviour of these periodicities are important and often cited as a

★E-mail: m.j.middleton@dur.ac.uk

means of identifying the nature of the source as a magnetic CV (although see Ramsay et al. 2008).

In this paper, we present the discovery of a new, persistent, IP using both *INTEGRAL* and *XMM–Newton* data to constrain the important spectral and timing characteristics. We explore the uncertainty in the distance estimate to this object based on the optical spectroscopy presented by Masetti et al. (2008) and find that the estimate of 7 kpc is probably incorrect given the absorbing material expected to be present in such systems.

2 DATA AND PREVIOUS ANALYSIS

The IR source 2MASS J180438.92−145647.4 has been identified by the *INTEGRAL* Galactic survey as a hard, X-ray-bright source of interest. Two optical investigations have followed, first by Burenin et al. (2006) who identify the counterpart as a massive star and then by Masetti et al. (2008) who identify it as a low-mass star. The latter assume that the extinction of 3 mag from optical line ratios is incorrect due to the large inferred distances that would result and instead determine a distance of ∼7 kpc (based on the Galactic colour excess). This suggests that the source is one of the very faintest low-mass X-ray binaries (LMXBs) and likely to therefore be a member of the very faint X-ray transients (VFXTs; see Muno et al. 2005b; Sakano et al. 2005; Wijnands et al. 2006; Degenaar & Wijnands 2009). However, the optical magnitude (18.7 in the *R* band) together with 3 mag of absorption would suggest an identification of the secondary with a giant star and therefore a high-mass X-ray binary (HMXB). If this is the case, then the distance estimate of 7 kpc would make it extremely faint (only $\sim 1 \times 10^{35}$ erg s^{-1}) for a HMXB (e.g. Grimm, Gilfanov & Sunyaev 2006), and would imply that we are looking at an object even more distant and on the far side of the Galactic bulge.

The source has been observed in the 0.2–10 keV X-ray band on three occasions, a short (1 ks) *Chandra* positional pointing (OBSID: 7275), an ∼12 ks pointed observation by *XMM–Newton* (OBSID: 0405390301, identifier: 2XMMi J180438.7−145647) and a follow-up *Swift* ToO (taken on 2011 March 9) which has confirmed that the source is persistent, thus effectively ruling out an identification with the subset of VFXTs. The source has also been observed by the higher energy X-ray detectors on-board *INTEGRAL* for a sum exposure time of ∼2500 ks taken over several years overlapping with the *XMM–Newton* observation. Given its proven persistent nature and the simple fact that the source would not be detected in the higher energy bandpass if in short-lived outburst (i.e. when a SSS), we include the data in our analysis as a contemporaneous description of the emission above 10 keV.

We extract the *XMM–Newton* data using SAS v10 and filter the imaging data using standard patterns (≤4 for PN and ≤12 for the MOS) and flags (=0). We proceed to remove hard proton flaring episodes from the full-field high-energy (>10 keV) light curve, leaving ∼10 ks of good data (this is the most conservative estimate of the good time interval, the source is actually much brighter than the background <10 keV for the full observation length of ∼12.6 ks), and proceed to extract spectra using XSELECT from circular source and background regions of 35-arcsec radius. Although the MOS2 central chip was turned off for the duration of the observation, both the MOS1 and PN were exposed for the full duration.

3 X-RAY SPECTRAL ANALYSIS

We fit the background-subtracted *XMM–Newton* data (grouped on a minimum of 25 counts per energy channel) together with the standard spectral *INTEGRAL* (ISGRI) products in XSPEC v 11.3.2 with a simple power law, absorbed by a neutral foreground column and a constant of proportionality to account for differences between the detector responses (in XSPEC, this is CONS*TBABS*POW). The resulting fit quality is very poor (χ^2 of 858.7 for 330 d.o.f.).

The reason for this poor fit is clear from the ratio plot shown in Fig. 1. Whilst the extremely hard ($\Gamma = 0.94^{+0.05}_{-0.03}$) power law is a good description of the underlying continuum below ∼6 keV (except at the lowest energies where there appears to be a soft excess), there is a large, broad iron emission feature followed by an obvious rollover below ∼20 keV. Adding a single Gaussian dramatically improves the fit quality ($\Delta\chi^2 \sim 345$ for 3 d.o.f.) giving a broad (σ = 0.35 keV) and strong [equivalent width (EQW) of ∼1.4 keV] line which peaks at 6.64 keV. The breadth of the line could be due to smeared reflection as seen in X-ray binaries (XRBs) at low mass accretion rates (see Fabian 2005); however, the spectral properties are inconsistent and the EQW of this feature is far larger than has been seen in any reflection-dominated XRB to date, suggesting an alternative origin. Instead we obtain a marginally better fit ($\Delta\chi^2 \sim$ 12 for 6 d.o.f.) by describing the excess as an iron triplet corresponding to lab-frame energies of ∼6.4, 6.65 and 6.95 keV. Together with the underlying, extremely hard continuum ($\Gamma \sim 1.00 \pm 0.05$), we then initially identify the source as an IP in the persistent dim, hard state. In this case, we would expect the spectrum to be dominated by bremsstrahlung cooling with a strong component of photoelectric absorption (Norton & Watson 1989) and reflected emission from the WD surface creating the strong 6.4-keV iron line (Beardmore et al. 1995; Done, Osborne & Beardmore 1995; Done & Magdziarz 1998).

We can provide a reasonable estimate for the physical description of the shock-heated plasma emission by assuming a model for a multitemperature flow with variable elemental abundances (CEVMKL).[1] In this case, the emission measure is weighted by a power law in temperature, with the single temperature parametrizing the model being the hottest temperature of the flow. Although not a true physical model, constraining this parameter will provide a reasonable estimate of the shock temperature. We combine this intrinsic emission with reflection from the surface of the WD (with a fixed incident spectral index of 1.5), all of which is obscured by a neutral partial covering fraction and a foreground Galactic column[2] [in XSPEC, this is CONS*TBABS*PCFABS*(REFXION[3] (CEVMKL))]. We find the requirement for a second neutral covering fraction ($\Delta\chi^2 \geq 100$ for 2 d.o.f.) although the inclusion of any further absorbers does not significantly improve the fit. We obtain an good description of the data (χ^2 of 346.5 for 325 d.o.f.) with the best-fitting model and residuals plotted together in Fig. 2 and the model parameters with 90 per cent confidence limits provided in Table 1 (note that, in this best-fitting case, the constants of proportionality are consistent within 10 per cent of unity). The model provides an estimate for the unabsorbed 0.3–10 keV flux of 2.4×10^{-11} erg cm^{-2} s^{-1}. This is fairly bright for an IP in the dim, hard state (although a distance of ∼2.5 kpc would be required in order for this to be the brightest; Stacey et al. 2011). However, whilst the source is relatively bright, the hard continuum precludes a useful

[1] See Singh, White & Drake (1996).

[2] We use an extrinsic column with an upper limit of 0.6×10^{22} cm^{-2} to be consistent with the estimates available from HEASARC (Dickey & Lockman 1990; Kalberla et al. 2005).

[3] This is a private model based on REFLBAL as described in Done & Gierliński (2006) but with the updated ionization tables of Ross & Fabian (2005).

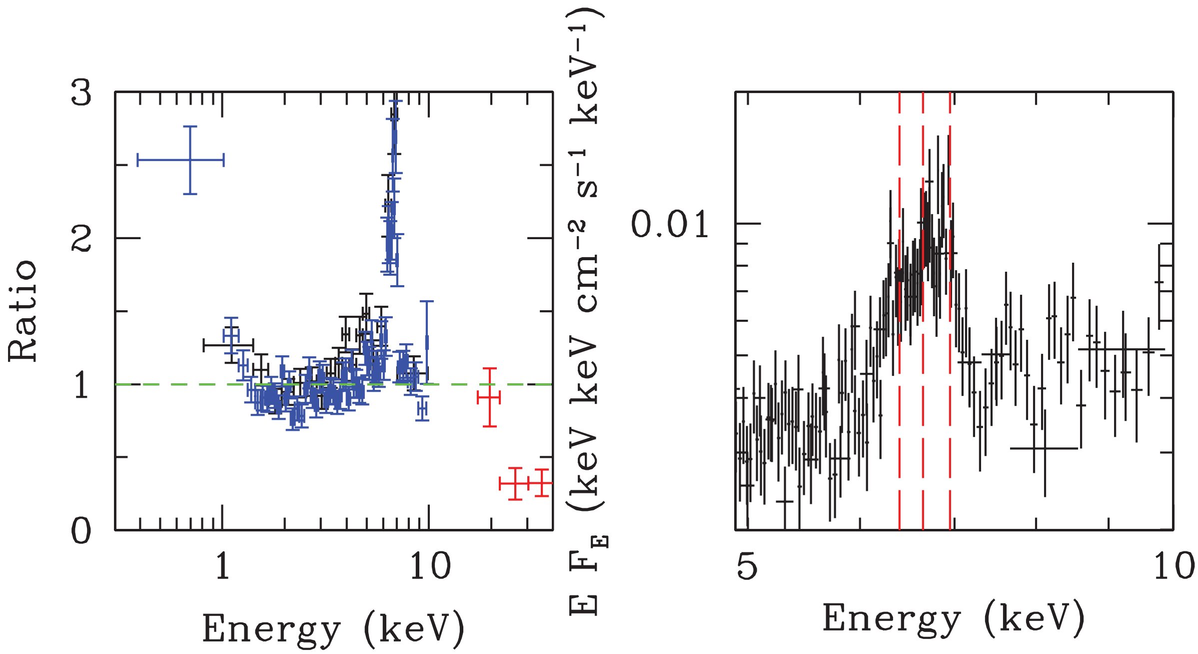

Figure 1. Left: ratio of the *XMM–Newton* (PN: blue and MOS1: black) and *INTEGRAL* data (ISGRI: red) to a model of an absorbed power law with a best-fitting index of ∼0.94. There are clear, strong residuals due to iron emission and the presence of a rollover in the spectrum below ∼20 keV. Right: the *XMM–Newton* data from 5 to 10 keV (unfolded through a power law of $\Gamma = 0$ and norm = 1) together with dashed vertical lines, indicating the rest-frame energies for the iron triplet (6.4, 6.65 and 6.95 keV, respectively).

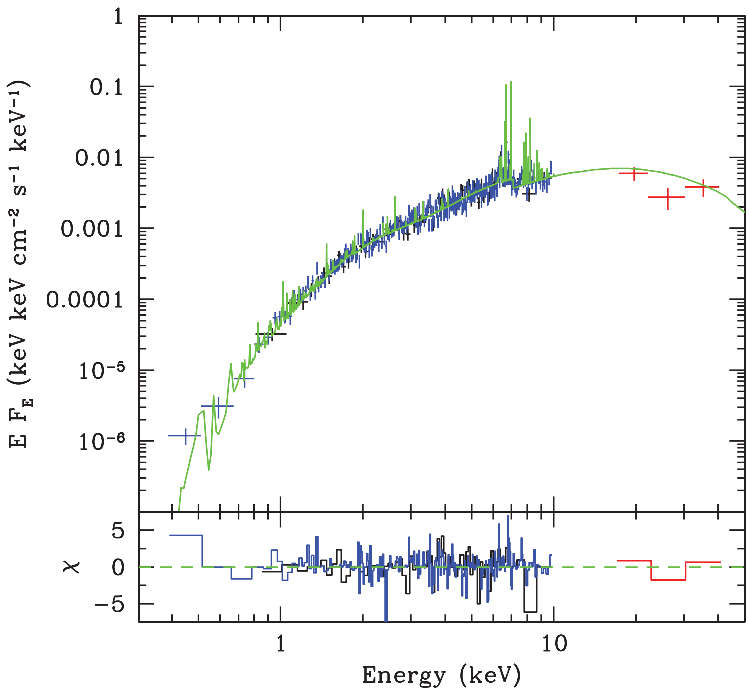

Figure 2. X-ray spectral data from the PN (blue) and MOS1 (black) together with the *INTEGRAL* ISGRI data (red). The best-fitting model comprising a cooling flow, reflection and absorption (see Table 1) is shown in green with residuals to this in the panel below.

RGS analysis which could help identify soft emission/absorption features (and identify the physical, multitemperature nature of the emission; Wu et al. 2003).

The strong iron feature in the spectrum (see Fig. 1) may be well described by a combination of three Gaussians (although the 6.4-keV line originates from reflection from the WD surface rather than intrinsic photo-electric emission from the plasma), and we obtain the properties of these by fitting the *XMM–Newton* data alone together with a simple absorbed power-law continuum. The best-fitting model parameters are also shown in Table 1. These show that, whilst the properties of the continuum are consistent with those seen for other IPs, the inferred EQWs of the iron lines are towards the upper limit of what has previously been observed (e.g. Butters et al. 2011). We note that due to the marginal improvement in fit quality

Table 1. Best-fitting spectral parameters.

CONS*TBABS$_1$*PCFABS$_1$*PCFABS$_2$[REFXION(CEVMKL)]	
$n_{\mathrm{H},1}$ ($\times 10^{22}$ cm^{-2})	$28.02^{+8.51}_{-6.88}$
Fraction$_1$	$0.67^{+0.05}_{-0.06}$
$n_{\mathrm{H},2}$ ($\times 10^{22}$ cm^{-2})	$1.85^{+0.42}_{-0.40}$
Fraction$_2$	$0.80^{+0.06}_{-0.03}$
logξ	$1.00^{+0.77}_{-\mathrm{peg}}$
kT_{max} (keV)	$23.30^{+8.84}_{-5.09}$
Fe abund	$0.67^{+0.25}_{-0.17}$
χ^2 (d.o.f.)	346.8 (324)
Null P	0.18
CONS*TBABS(POWERLAW+GAUSS$_1$+GAUSS$_2$+GAUSS$_3$)	
$n_{\mathrm{H},1}$ ($\times 10^{22}$ cm^{-2})	$0.81^{+0.06}_{-0.07}$
Line energy$_1$ (keV)	6.41 ± 0.06
EQW$_1$ (eV)	244
σ_1 (keV)	0.16
Line energy$_2$ (keV)	6.69 ± 0.04
EQW$_2$ (eV)	99
σ_2 (keV)	3.8×10^{-4}
Line energy$_3$ (keV)	6.91 ± 0.05
EQW$_3$ (eV)	324
σ_3 (keV)	7.2×10^{-2}
Γ	0.67 ± 0.05
Norm	$3.2 \times 10^{-4} \pm 0.2 \times 10^{-4}$
χ^2 (d.o.f.)	353.7 (316)
Null P	0.07

Notes. The best-fitting parameter values are given with 90 per cent confidence limits, with the properties of the iron lines obtained separately to those of the continuum. Note that the ionization parameter (logξ) is set to peg at a lower limit of 1.

from including three Gaussians over a single component, obtaining constraining estimates for the errors on the strength (EQW) and breadth (σ) is unrealistic and so are omitted.

To ensure that cross-calibration errors are not overly influencing the best-fitting model parameters, we test the upper and lower limits for the constant of proportionality to the *INTEGRAL* data ($\sim 1.03 \pm 0.4$ – consistent with the cross-calibration status of EPIC versus ISGRI).[4] In both cases, we obtain values for the temperature of the rollover within the 90 per cent confidence limits presented in Table 1. This rollover in the spectrum, due to the peak temperature of the plasma emission, can then be used as a crude measure for the mass of the WD. Aizu (1973) gives a formula relating the gravitational potential of the WD to the mass and radius:

$$kT_{\mathrm{s}} = 16 \times \left(\frac{M}{0.5\,\mathrm{M}_{\odot}}\right)\left(\frac{R}{10^9\,\mathrm{cm}}\right)^{-1}\ \mathrm{keV}. \qquad (1)$$

Substituting the analytical expression for the radius (Nauenberg 1972),

$$R = 0.78 \times 10^9 \left[\left(\frac{1.44\,\mathrm{M}_{\odot}}{M}\right)^{2/3} - \left(\frac{M}{1.44\,\mathrm{M}_{\odot}}\right)^{2/3}\right]^{1/2}\ \mathrm{cm}, \qquad (2)$$

[4] See Kirsch et al. (2004) and http://heasarc.nasa.gov/docs/heasarc/caldb/caldb_xcal.html. For examples of this in use, see e.g. Caballero-García et al. (2009).

allows us to calculate the mass of the WD from the shock temperature:

$$\frac{M_{\mathrm{WD}}}{\mathrm{M}_{\odot}} = 1.44 \times \left[\frac{1}{2}\left(1 + \sqrt{1 + 4 \times \left(\frac{59}{kT_{\mathrm{s}}}\right)^2}\right)\right]^{-3/4}. \qquad (3)$$

Taking the best-fitting value for kT_{s} from our model ($23.30^{+8.84}_{-5.09}$ keV), this gives a mass of $0.62^{+0.13}_{-0.09}\,\mathrm{M}_{\odot}$, assuming that the maximum temperature of the plasma emission model is a reasonable approximation to the shock temperature. Based on the correction factor expected from the change in the gravitational potential over the shock height (Cropper, Ramsay & Wu 1998; Cropper et al. 1999), this provides an estimate for the mass of $\sim 0.60\,\mathrm{M}_{\odot}$, consistent with the median mass of isolated WDs (Kepler et al. 2007).

An important consequence of this identification is that there is a clear prediction for the presence of large columns of material that obscure the intrinsic emission (see Cropper 1990). This therefore makes any associated optical identification and distance estimate based on line spectra highly unreliable as the intervening material will distort the emission. Instead, in order for the source to have similar luminosities to those of other IPs in the dim, hard state, we expect the distance to be < 2.5 kpc.

4 TIMING ANALYSIS

There is a wealth of evidence suggesting the presence of periodicities from the optical and X-ray light curves of IPs, attributed to either the orbital period of the secondary or the spin period of the WD.[5] The properties of the broad-band noise on which these periodicities sit in the power density spectrum (PDS) has been of great interest as the behaviour can provide observational tests for theories of how non-linear variability is generated in the accretion process (see e.g. the discussion of Uttley, McHardy & Vaughan 2005). In the case of XRBs, this is now widely accepted to be due to propagating fluctuations in the disc (see Lyubarskii 1997; Arévalo & Uttley 2006; Ingram & Done 2011). However, in the case of IPs, the inner regions of the inflow are disrupted by the magnetic field of the WD, leading to a large truncation radius of the accretion disc, within which, the material follows the magnetic field lines. There is therefore the prediction of a break in the PDS (beyond which the red noise follows $\sim\nu^{-2}$; Revnivtsev et al. 2010) which has now been observationally confirmed (Revnivtsev et al. 2009b, 2010). Due to this break at low frequencies, there is very little rapid variability, unlike in the cases of XRBs where significant rapid variability can be created by the magnetorotational instability (MRI; see Beckwith, Armitage & Simon 2011) being established in a low-density flow (Done, Gierliński & Kubota 2007). In the cases where the accretion flow is stream-fed (e.g. V2400 Oph), the lack of broad-band noise is evidently due to the observational lack of an accretion disc (Hellier & Beardmore 2002). The position of the truncation radius and the nature of the accretion are therefore paramount in accurately determining the presence of periodicities. For example, where the disc truncates at very large radii (i.e. effectively stream-fed), there is the prediction that, at high frequencies, there should be little or no red noise in the PDS, making significance tests here rather ambiguous (see the discussion of Vaughan 2005). However, where the statistical quality of the data allows, and there is a clear (and stringently tested) lack of broad-band red noise, there may be an argument for a significance test to be carried out above the white

[5] http://asd.gsfc.nasa.gov/Koji.Mukai/iphome/catalog/members.html

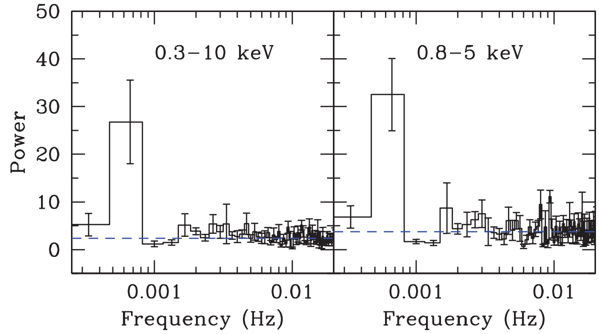

Figure 3. Average PDS extracted from the 0.3–10 keV (left) and 0.8–5 keV (right) light curves binned on 10 s, made from five segments of the light curve including the white noise (horizontal dashed line). There is an excess of variance at ∼0.7 mHz which is significant at $>3\sigma$ in the 0.8–5 keV band. As the power over the remaining observable frequency bins is consistent with the statistical white noise (possibly indicating the source as being stream-fed), this is an acceptable method for determining the significance of this feature.

noise. In such a situation, observing the behaviour of the spectra binned on the period may allow for a second-order test (see the following section).

Although we do not have any simultaneous optical data, the identification of an X-ray periodicity may help further constrain the identification with an IP. We extract the 0.3–10 keV, co-added (using the PN and MOS1 with the same start and stop times), background-subtracted light curve, binned on 10 s, using the same regions as the spectral analysis. As the source dominates the background emission throughout the observation, we use the full observation length in order to improve any variability constraints. We initially test the shape of the broad-band variability out to the longest available time-scales using the most robust least-squares (LS) method available (Vaughan 2010) and find that the broad-band continuum is consistent with the white noise at the 3σ level (although we identify a possible peak of excess variance at ∼0.7 mHz). Although we cannot probe down to very low frequencies, the fairly high data quality from this observation would imply that we should see variability power on these frequencies if there was a contribution from disc accretion (Revnivtsev et al. 2010). This suggests that we are observing a stream-fed IP similar to V2400 Oph (Norton, Haswell & Wynn 2004) which is seen to possess a similar broad-band X-ray spectrum (Revnivtsev et al. 2004). This lack of broad-band noise therefore allows us to obtain tentative significance measurements assuming a white noise description of the continuum variability. We proceed to extract the PDS using the FTOOL: POWSPEC in units of fractional rms^2. We extract the PDS averaged over five segments of the light curve in order to realistically constrain any bins of variability. We again find an excess of variance at ∼0.7 mHz with the tightest constraints in the 0.8–5 keV band at a significance $>3\sigma$ (see Fig. 3). We note that the coherence of this excess variance ($\nu_{\rm QPO}/\nu_{\rm FWHM}$) is rather low, preventing a robust identification with a period/quasi-period (although the behaviour of the broad-band noise is unlikely to facilitate an identification with a break in the PDS); however a period of ∼24 min could be readily associated with the spin period of the WD and is similar to that of V2306 Cyg (Norton et al. 2002) at similar flux levels.

4.1 Phase-binned spectroscopy

We can better confirm the nature of the excess variance by extracting the spectral properties in the peaks and troughs of the light curve. This phase-binned spectroscopy has been applied to a number of IPs with confirmed spin periods (e.g. Done et al. 1995; Hellier et al. 1996; Pekön & Balman 2011) and, in each case, the troughs are found to have harder spectra due to the changing proportions of reflection and absorption.

We follow a similar approach and extract PN spectra from epochs corresponding to the peaks and troughs ensuring no overlap between the two and avoiding the flaring episodes as with the time-averaged spectroscopy. This gives a total exposure of 3.8 ks for the peaks and 5.7 ks for the troughs. To identify any changes in continuum shape, we apply a simple power-law model to both sets of data simultaneously [TBABS(POWERLAW)] over the 0.3–6 keV band (to ignore the distorting effects of the iron emission]. We obtain best-fitting spectral index values of $0.32^{+0.12}_{-0.12}$ and $0.57^{+0.15}_{-0.14}$ for the troughs and peaks, respectively, and an improvement in $\Delta\chi^2$ of ∼4.8 for 1 d.o.f. over fixing the index to be the same in both. This allows us to claim that the spectrum of the troughs appears harder, consistent with the behaviour of other IPs in the dipping phase of their spin period. We attempt to quantify the changing properties of the iron emission by fixing the continuum to the best-fitting value below 6 keV and including three Gaussian components in the model. However, the much shorter exposure for each phase-binned spectrum prevents any difference from being well constrained.

5 CONCLUSION

The hard, bright X-ray source, 2XMMi J180438.7−145647, has been observed only once by *XMM–Newton*; however, together with the available *INTEGRAL* (ISGRI) data, this relatively short observation has shown that the time-averaged X-ray emission is characteristic of an IP. In general, we determine similar properties for this source when we compare them with that of the wider population of IPs, save for the iron features which are notably strong. It is possible that any future, longer observation may be able to use this strong iron triplet to provide a better diagnostic of the plasma region.

Due to the extremely hard X-ray spectrum and short observation length, we cannot obtain a useful RGS spectrum, precluding a detailed analysis of the complex (multitemperature) nature of the plasma. However, the inclusion of *INTEGRAL* (ISGRI) data has allowed us to place constraints on the peak temperature of the plasma flow. Taking into account the changing gravitational potential over the shock height, this provides an estimate for the mass of the WD of $\sim 0.60\,{\rm M}_{\odot}$, consistent with the median of isolated WD masses.

We detect the presence of excess variance power at ∼0.7 mHz which *may* be associated with the spin period of the WD. Phase binning the emission produces spectra which show behaviour consistent with that of other IPs, supporting this identification for the source. The lack of variability, aside from this feature, suggests that we are observing a stream-fed IP, similar in behaviour to V2400 Oph.

Given the large columns of absorbing material enshrouding IPs, we find the distance estimate based on the optical spectrum (Masetti et al. 2008) to be highly unreliable. Instead, given the flux of the source, its distance is much more likely to be <2.5 kpc to be consistent with the observed luminosities of other IPs.

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