Modelling the effect of absorption from the interstellar medium on transient black hole X-ray binaries

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ABSTRACT
All observations of Galactic X-ray binaries are affected by absorption from gas and dust in the interstellar medium (ISM) which imprints narrow (line) and broad (photoelectric edges) features on the continuum emission spectrum of the binary. Any spectral model used to fit data from a Galactic X-ray binary must therefore take account of these features; when the absorption is strong (as for most Galactic sources) it becomes important to accurately model the ISM absorption in order to obtain unbiased estimates of the parameters of the (emission) spectrum of the binary system. In this paper, we present analysis of some of the best spectroscopic data from the XMM–Newton RGS instrument using the most up-to-date photoabsorption model of the gaseous ISM $\text{ISM}_{\text{abs}}$. We calculate column densities for H, O, Ne and Fe for seven transient black hole X-ray binary systems. We find that the hydrogen column densities in particular can vary greatly from those presented elsewhere in the literature. We assess the impact of using inaccurate column densities and older X-ray absorption models on spectral analysis using simulated data. We find that poor treatment of absorption can lead to large biases in inferred disc properties and that an independent analysis of absorption parameters can be used to alleviate such issues.

Key words: accretion, accretion discs – black hole physics – ISM: abundances – X-rays: binaries.

1 INTRODUCTION
Low-mass X-ray binaries (LMXBs) are systems composed of a black hole (BH) or neutron star (NS), often called the primary, and a secondary low-mass donor star usually of mass $\lesssim 1.5 \times 10^3 \, M_\odot$. Material is transferred from the secondary via Roche Lobe overflow towards the primary and forms an accretion disc around the central compact object (Shakura & Sunyaev 1973; McClintock & Remillard 2006; Done, Gierliński & Kubota 2007). An outwards transfer of angular momentum causes a flow of material towards the BH/NS, resulting in a huge amount of energy being produced in the form of X-rays.

In this paper, we will focus exclusively on Galactic LMXBs with a BH primary (henceforth called BH XRBs). Most BH XRBs spend the majority of their lives in a low-luminosity quiescent state with X-ray luminosity less than $L_X \sim 10^{31} \, \text{erg s}^{-1}$ and a small mass accretion rate on to the BH. However, occasionally these objects are seen to go into outburst reaching X-ray luminosities of order $10^{36} \sim 10^{39} \, \text{erg s}^{-1}$. During outburst the properties of the observed X-ray spectra change over time but can roughly be thought to belong to two main ‘states’, the soft and hard states.

The soft state (also sometimes referred to as the thermal-dominated state) shows an X-ray spectrum dominated by thermal emission originating from the accretion disc with a temperature $T_{\text{peak}} \sim 1 \, \text{keV}$ (Remillard & McClintock 2006), and a weaker high energy tail with a non-thermal spectrum extending up to $\sim 100 \, \text{keV}$. Soft states tend to occur near the peak of the outburst and a transient source may remain in the soft state for weeks and months. Sources in the soft state also tend to show weaker (or absent) radio emissions and suppressed rapid X-ray variability.

By contrast, the hard state is generally seen during quiescence or during the rise and decay of outbursts (Done et al. 2007; Belloni 2010). It is characterized by the spectrum dominated by non-thermal (power-law) emission, which extends up to energies of around $100 \, \text{keV}$, and a much weaker thermal component. The timing and radio properties are also different showing strong, rapid X-ray variability (van der Klis 2006; Belloni 2010) and persistent radio properties (Fender, Homan & Belloni 2009). The origin of this non-thermal emission is generally thought to either be inverse-Compton scattering (of soft photons emitted from the accretion disc) in a corona of hot electrons located near the inner regions of the accretion flow (Haardt & Maraschi 1993; Dove, Wilms & Begelman 1997; Poutanen 1998), or synchrotron and self-Compton emission produced in the base of the radio jet (Markoff, Falcke & Fender 2001; Markoff, Nowak & Wilms 2005).
Modelling the observed X-ray spectra of these systems requires combining several spectral components. The two dominant emission components are a thermal (blackbody-like) emission spectrum from the accretion disc and non-thermal (power law-like) emission spectrum from the corona. The relative strengths of these two distinguish between the soft and hard states. The third component is ‘reflection’ (Fabian et al. 1989; Reynolds & Novak 2003; Dauser et al. 2010). Finally, there is absorption, as photons pass through gas and dust in the interstellar medium (ISM), imprinting features in the observed X-ray spectrum.

Many analyses of the composition of the ISM have been performed in recent years since the launch of XMM–Newton and Chandra, both of which are equipped with high resolution X-ray spectrometers. The results of these studies indicate the presence of a multiphase ISM structure: a cold phase of a mixture of dust, molecules and mostly neutral gas at <104 K, a warm phase of weakly ionized gases at ~104 K and a more highly ionized hot phase at ~105 K (Takei et al. 2002; Yao et al. 2009; Liao, Zhang & Yao 2013; Pinto et al. 2013; Gatuzz et al. 2016).

A variety of photoabsorption models have been used in the past. For example, wabs, which uses relatively simple photoelectric cross-section models from Morrison & McCammon (1983), solar abundances from Anders & Ebihara (1982) but had no contributions from ions, molecules and grains, and only allowed the column density of hydrogen as a free parameter. The model Phabs (Balucinska-Church & McCammon 1992) remedied the latter issue, with adjustable abundances for 17 elements. With revised cross-sections and abundances, TReabs (Wilms, Allen & McCray 2000) provided a further improvement, also including the effects of grains and H2 molecules, but still only considered neutral atomic species. The ability to also include ionized species is one of the key advantages of the model used in this study, ISMabs (Gatuzz et al. 2015), along with its data base of the most accurate atomic data available for neutrally, single and doubly ionized species of 11 elements.

Absorption from the ISM affects all X-ray observations. In order to better study the X-ray emission spectra of BH XRBs, it would be useful to have both absorption models which account for both neutral and ionized species, accurate atomic data, and accurate column densities for each target source. A list such as this would allow one to quickly and accurately incorporate absorption into spectral analysis by simply selecting the best publicly available model and inserting the necessary abundances. Gatuzz et al. (2016) already provide this function for a number of BH and NS systems, here we expand on the number of BH sources. The 21 cm maps (Dickey & Lockman 1990; Kalberla et al. 2005; Willingale et al. 2013) are often used in a similar fashion, with many published spectral analyses using the hydrogen column densities found in these surveys. However, there is evidence to suggest that much of the absorption from LMXBs originates from hot gases intrinsic to the sources (Gatuzz, Garcia & Mendoza 2014; Luo & Fang 2014). There has also been a suggestion that the column density is related to spectral states (Cabanac et al. 2009). In this paper, we present an analysis of XMM–Newton data for a number of BH XRBs, attempt to assess the impact of a poor choice of absorption model and parameters on spectral analysis of such systems, and test the feasibility of using a single set of column densities for any given system regardless of the time of observation. The structure of the paper is as follows: details of the data reduction can be found in Section 2, the procedure and results of the analysis in Sections 3 and 4 and a discussion of the results in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

XMM–Newton (Jansen et al. 2001) operates in a high elliptical orbit of ~2 d and carries three co-aligned X-ray telescopes, with three EPIC imaging spectrometers (Strüder et al. 2001), two RGS reflection grating arrays (den Herder et al. 2001) and a single optical monitor (Mason et al. 2001). Here, we are primarily concerned with the data from the RGS instrument; in a companion paper (Eckersall et al. in preparation), we will discuss the corresponding EPIC broadband X-ray spectra.

In total, we have processed data for 96 observations from 35 different systems. These represent all publicly available observations of BH XRBs up until 2015 September 30. Table A1 contains all the information on the observations included in this study, along with the system parameters (mass of primary, distance and inclination) used in the RGS fitting (values taken from Tetarenko et al. (2016) and references therein, and from Froning et al. (2014)). If not known, we assume a mass of 10 M⊙, a distance of 5 kpc and a disc inclination of 50°.

The processing of the raw observational data files (ODFs) was achieved using the standard processing chains with the XMM–Newton Science Analysis Software (sas V14.0.0) and the current calibration files. We extracted RGS spectra for all observations over our sample of systems. Source and background spectral files and responses were generated using rgsproc v1.34.7. The spectra from RGS1 and RGS2, along with separate exposures within each observation, were combined together using rgscombine v1.3.4. The tool specgroupl v1.6 was then used to group the spectra such that each bin is not narrower than one-third of the instrumental (FWHM) energy resolution.

Here, we examine only the first-order spectra with a count rate above 1.0 counts−1, all those below this are labelled as faint in Table A1 and rejected from the sample. Some of the observations were bright enough that pile-up became an issue. Because of this, a number of the observations (e.g. Swift J1753.5−0127 rev2979) have been excluded from the RGS analysis.

3 RESULTS

3.1 RGS spectral fitting

We fit spectra from each source using xspec 12.9.0. We use ISMabs (Gatuzz et al. 2015) to model the absorption. This model includes photoabsorption from both neutral and ionized species of a number of cosmically abundant elements. Although the model includes elements such as N, Mg, Si and S, the aim of this analysis is to get a fit of the ISM absorption properties independent from the EPIC analysis, not to get a complete model for all features. We therefore fitted column densities of H, O, Ne and Fe, as these have the strongest effect on the shape of the soft X-ray absorption (the He abundance is fixed as this parameter is degenerate with the H column density). The ISMabs model also includes singly and doubly ionized species, so the effects of OII, OIII, NeII and NeIII will also be taken into consideration. All the other elemental abundances (e.g. C, N, Si, S, Ar, Ca) were tied to N(H) so that their relative abundances are equal to the ISM data in Wilms et al. (2000). Contributions from the highly ionized hot gas component of the ISM have been found to be very small and so are not included here (Gatuzz et al. 2013a,b; Luo & Fang 2014).

To provide the soft X-ray continuum expected for a black hole X-ray binary, we used the model ISMabs*(SIMPL*KERRBB). SIMPL (Steiner et al. 2009) computes a non-thermal spectrum with
Figure 1. XMM–Newton RGS spectrum of the source GX 339–4 (rev0782) and the residuals. The key atomic features being modelled are labelled.

<table>
<thead>
<tr>
<th>System name</th>
<th>$N$(H)</th>
<th>$N$(O)</th>
<th>$N$(O)</th>
<th>$N$(Ne)</th>
<th>$N$(Ne)</th>
<th>$N$(Ne)</th>
<th>$N$(Ne)</th>
<th>$N$(Fe)</th>
<th>C-stat(dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRO J1655–40</td>
<td>0.73 ± 0.01</td>
<td>467.4 ± 5.5</td>
<td>5.67 ± 2.92</td>
<td>9.53 ± 3.99</td>
<td>106.2 ± 2.3</td>
<td>17.3 ± 2.1</td>
<td>1.81 ± 0.35</td>
<td>21.8 ± 0.4</td>
<td>3016(950)</td>
</tr>
<tr>
<td>GS 1354–64</td>
<td>0.694 ± 0.014</td>
<td>443.9 ± 13.5</td>
<td>–</td>
<td>–</td>
<td>74.5 ± 7.8</td>
<td>28.6 ± 6.6</td>
<td>–</td>
<td>15.7 ± 1.3</td>
<td>416(316)</td>
</tr>
<tr>
<td>GX 339–4 rev0782</td>
<td>0.561 ± 0.057</td>
<td>334.9 ± 7.6</td>
<td>11.4 ± 4.1</td>
<td>12.5 ± 2.8</td>
<td>40.9 ± 1.9</td>
<td>16.6 ± 1.4</td>
<td>2.41 ± 0.58</td>
<td>17.2 ± 0.4</td>
<td>1093(311)</td>
</tr>
<tr>
<td>rev0514</td>
<td>0.55 ± 0.007</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1375(317)</td>
</tr>
<tr>
<td>rev1318</td>
<td>0.54 ± 0.013</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>689(317)</td>
</tr>
<tr>
<td>rev1325</td>
<td>0.53 ± 0.013</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>582(314)</td>
</tr>
<tr>
<td>rev1338</td>
<td>0.53 ± 0.014</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>499(316)</td>
</tr>
<tr>
<td>rev1702</td>
<td>0.589 ± 0.025</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>396(314)</td>
</tr>
<tr>
<td>rev1886</td>
<td>0.554 ± 0.008</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>953(315)</td>
</tr>
<tr>
<td>rev2879</td>
<td>0.544 ± 0.018</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>578(315)</td>
</tr>
<tr>
<td>Swift J174510.8–262411</td>
<td>1.19 ± 0.02</td>
<td>503.0 ± 36.9</td>
<td>–</td>
<td>–</td>
<td>405.3 ± 28.5</td>
<td>232.1 ± 6.4</td>
<td>34.3 ± 6.4</td>
<td>5.77 ± 1.87</td>
<td>39.3 ± 1.5</td>
</tr>
<tr>
<td>Swift J1753.5–0127</td>
<td>0.275 ± 0.005</td>
<td>165.6 ± 5.07</td>
<td>1.87 ± 0.93</td>
<td>3.53 ± 0.74</td>
<td>21.2 ± 2.7</td>
<td>4.64 ± 1.36</td>
<td>0.98 ± 0.45</td>
<td>5.58 ± 0.56</td>
<td>1983(1240)</td>
</tr>
<tr>
<td>XTE J1720–318</td>
<td>1.27 ± 0.14</td>
<td>770.7 ± 59.9</td>
<td>–</td>
<td>–</td>
<td>168.1 ± 9.8</td>
<td>33.9 ± 8.2</td>
<td>–</td>
<td>34.2 ± 3.8</td>
<td>496(314)</td>
</tr>
<tr>
<td>XTE J1752–223</td>
<td>0.71 ± 0.01</td>
<td>361.5 ± 6.0</td>
<td>–</td>
<td>5.49 ± 2.95</td>
<td>104.2 ± 3.7</td>
<td>30.2 ± 3.1</td>
<td>3.60 ± 1.22</td>
<td>13.9 ± 0.7</td>
<td>960(313)</td>
</tr>
</tbody>
</table>

Table 1. Column densities values from ISMabs. $N$(H) is in units of $10^{22}$ cm$^{-2}$, while the metals are in units of $10^{16}$ cm$^{-2}$.

an approximately power-law form, as might be expected from the inverse-Compton scattering of soft photons from the disc; by removing a fraction ($f_{\text{scat}}$) of photons from the observed disc spectrum and ‘scatters’ them into a power law extended to high energies. KERRBB (Li et al. 2014) models the disc spectrum, providing a multitemperature blackbody model for a thin disc around a Kerr BH. The photon index and scattering fraction from SIMPL and the mass accretion rate from KERRBB were allowed to vary for each individual spectrum, with SIMPL allowing both up- and down-scattering. Mass, distance and inclination are fixed at the values stated in Table A1. In KERRBB, $\eta$, the ratio of disc power produced by a torque at the inner disc boundary to the disc power arising from accretion, we chose to set to 0, and the spectral hardening fraction, $f_{\text{col}}$, is fixed at 1.7. The effects of self-irradiation and limb-darkening are included. We have chosen to neglect the reflection component as it is a weak feature in our chosen wavelength range. At this stage, the purpose of the model is not to produce the physically plausible broad-band spectrum for a BH XRB, but to capture the basic shape of the soft X-ray continuum.

The data were fitted over a wavelength range of 11–24 Å. Many of the observations have poor signal-to-noise outside of this range. We tried extending the fitted range up to 30 Å for a small number of the sample and found that the $N$(H) values were consistent with those from the smaller wavelength range. $N$(H) is allowed to vary independently for each observation, while the abundances for O, Ne and Fe are fitted such that their abundances relative to hydrogen are kept constant across all observations.

An example of a fitted spectrum is shown in Fig. 1 with the remainder in the Appendix. The majority of the observations detailed in Table A1 have a signal-to-noise ratio too low for any useful analysis and so were dropped from this part of the study. For all the remaining sources with good data quality the values found for the column densities of the fitted elements can be seen in Table 1. In almost all cases, the model is able to capture the main features of the data, leaving residuals of <10 per cent and usually much smaller. Due to the high quality of the data though, the fit statistics were often unacceptable (using a $\chi^2$ test) even when the residuals were small in an absolute sense. In a few cases (e.g. GRO J1655–40, GX 339–4), there are clear systematic residuals around the Fe–L region (17–18 Å) indicating that the model does not fully capture the complexity of the iron absorption.
3.2 GX 339–4

The system GX 339–4 has the largest number of observations in our sample, allowing us to test the time dependence of the column densities. We have a total of eight RGS spectra from GX 339–4 taken over 13 yr with a mix of soft and hard states. We initially fit the observation at rev0782 (which is merged with rev0783 to create a total exposure time of 250 ks) in the same way as the other systems. We then fit the remaining seven observations with the N\textsubscript{H} free, but now with the O, Ne and Fe column densities fixed so that their relative abundances are equal to those of the rev0782 spectrum. The column densities for all eight fits are found in Table 1.

3.3 Comparison of hydrogen column density

We can compare the N\textsubscript{H} values found in our RGS fitting with those found through other methods to judge how realistic they might be. The first of these methods is the use of 21 cm radio maps, as in Dickey & Lockman (1990) and Kalberla et al. (2005). However, these are sensitive to just atomic, neutral hydrogen. Willingale et al. (2013) use X-ray observations of gamma-ray bursts to estimate N\textsubscript{H}, with the key difference being that they derive an empirical relationship between molecular (H\textsubscript{2}) and atomic hydrogen. Molecular hydrogen does contribute significantly to X-ray absorption, so this allows for a more accurate total measurement of the column density. Table 2 shows the N\textsubscript{H} values for the three 21 cm surveys, along with the X\textsubscript{MM}\textsubscript{abs} hydrogen column densities found in this paper and in Gatuzz et al. (2016), another recent study of X-ray absorption in XRBs using the same absorption model and a similar method. H column density estimates at any point on the sky based on the 21 cm maps are weighted averages of nearby measurements, typically within 1° of the target position.

Table 2. Comparison of N(H) values in units of 10\textsuperscript{22} cm\textsuperscript{-2}.

<table>
<thead>
<tr>
<th>System name</th>
<th>N\textsubscript{H}</th>
<th>21 cm survey\textsuperscript{a}</th>
<th>21 cm survey\textsuperscript{b}</th>
<th>21 cm survey\textsuperscript{c}</th>
<th>N\textsubscript{H}\textsuperscript{d}</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRO J1655–40</td>
<td>0.730 ± 0.010</td>
<td>0.684</td>
<td>0.578</td>
<td>0.722</td>
<td>0.784 ± 0.029</td>
</tr>
<tr>
<td>GS 1354–64</td>
<td>0.827 ± 0.017</td>
<td>0.914</td>
<td>0.727</td>
<td>0.871</td>
<td>–</td>
</tr>
<tr>
<td>GX 339–4</td>
<td>0.551 ± 0.057</td>
<td>0.526</td>
<td>0.374</td>
<td>0.518</td>
<td>0.41 ± 0.5</td>
</tr>
<tr>
<td>Swift J174510.8–262411</td>
<td>1.19 ± 0.02</td>
<td>0.659</td>
<td>0.652</td>
<td>0.796</td>
<td>–</td>
</tr>
<tr>
<td>Swift J1753.5–0127</td>
<td>0.275 ± 0.005</td>
<td>0.164</td>
<td>0.166</td>
<td>0.298</td>
<td>0.001 ± 0.026</td>
</tr>
<tr>
<td>XTE J1720–318</td>
<td>1.27 ± 0.14</td>
<td>0.477</td>
<td>0.525</td>
<td>0.635</td>
<td>–</td>
</tr>
<tr>
<td>XTE J1752–223</td>
<td>0.710 ± 0.011</td>
<td>0.454</td>
<td>0.456</td>
<td>0.600</td>
<td>–</td>
</tr>
</tbody>
</table>

Notes. \textsuperscript{a}Dickey & Lockman (1990); \textsuperscript{b}Kalberla et al. (2005); \textsuperscript{c}Willingale et al. (2013) and \textsuperscript{d}Gatuzz et al. (2016).

4 THE EFFECT OF INCORRECT ABSORPTION ESTIMATES ON DISC PARAMETERS

The majority of spectral analysis of LMXBs in the literature will have been performed with absorption models and column densities different from those presented in this work. If we are to compare disc parameters found from our results with those using an older model or N\textsubscript{H} estimates from the 21 cm maps for instance, then we need to be aware of any systematic biases originating from an incorrect treatment of absorption. For example, the inner radius of the accretion disc is often estimated from spectral fitting so a bias in the disc temperature caused by the use of an unsuitable model or column densities would lead to an inaccurate measure of the disc surface area.

To test this, we fit our model to simulated energy spectra. We used the XSPEC tool \texttt{fakeit} which – given a spectral model and relevant response matrix data – returns a simulated energy spectrum. Here, we used the response files from a XMM–Newton EPIC-pn observation of Swift J1753.5–0127. The exposure time of the simulated observation is set at 40 ks. The parameters for the continuum are set to numbers typical for each state. For the hard state: $\Gamma = 1.7$, $f_{\text{esc}} = 0.5$, $m = 0.1 \times 10^{18}$ g s$^{-1}$ and $f_{\text{col}} = 1.5$ and in the soft state: $\Gamma = 2.5$, $f_{\text{esc}} = 0.1$, $m = 1.0 \times 10^{18}$ g s$^{-1}$ and $f_{\text{col}} = 2.0$. For the X\textsubscript{MM}\textsubscript{abs} parameters, we select three different N\textsubscript{H} values: 0.3, 0.9 and 1.5 $\times 10^{22}$ cm$^{-2}$. These three N\textsubscript{H} values extend the study to test both heavily and lightly absorbed sources. This gives six spectra in total, a soft and a hard state for each N\textsubscript{H} value. The column densities for O, Ne and Fe are set such that the relative abundances match those in Wilms et al. (2000).

We then fit the model of \texttt{WABS* (SIMPL*KERRBB)} to each of these simulated spectra over an energy range of 0.8–10.0 keV and calculate the disc parameters as a function of the hydrogen column density inputted and frozen into \texttt{wabs}. We chose five different N\textsubscript{H} values to fit to each simulated spectra. Given the range of N\textsubscript{H} values to fit be it impossible to choose a set of five values that would be suitable in all cases, so instead they were decided separately, in such a way that the spread represents the range of values in which a well-constrained fit is still possible. The plots showing the free parameter values are shown in Fig. 2. We also performed one fit for each simulated N\textsubscript{H} value where we allowed the fitted N\textsubscript{H} value to go free, the results of these fits can be seen on the plots as the larger data points.

In these fits with N\textsubscript{H} allowed to vary, we can test the degeneracies between the hydrogen column density and the other free parameters by performing Markov Chain Monte Carlo (MCMC) analysis. We make use of the ‘emcee’ \texttt{Python} code (Foreman-Mackey et al. 2013) to complete this analysis. We use the Goodman–Weare algorithm with 100 walkers each performing 1000 iterations (in each case an additional 100 are performed first and ignored – this is the ‘burn in’ period). The initial distribution of the walkers is determined by the best-fitting value found by \texttt{xspec}. A contour plot with the results for the N\textsubscript{H} = 0.3 $\times 10^{22}$ cm$^{-2}$ hard state spectrum can be seen in Fig. 3 [this plot is created using the ‘corner’ \texttt{Python} code (Foreman-Mackey 2016)].

4.1 The effect of dust

X\textsubscript{MM}\textsubscript{abs} is a model which only includes the affects of the atomic and gaseous ISM, it does not include contributions from dust and molecules. Some studies (e.g. Pinto et al. 2010, 2013) have suggested that a significant amount of O I and Fe I is found in dust, so it would be useful to understand the effect of not including solids on the determination of the disc parameters. To do this, we made use of the model \texttt{TBvarabs}, which includes absorption from grains...
Overall, we find the model is capable of adequately fitting the majority of the features of the RGS spectra, with the most significant residuals appearing around the Fe and O edges at ~17 and ~23 Å, respectively. One possible explanation is dust: the model we have fitted only accounts for absorption due to the gaseous ISM. Pinto et al. (2010, 2013) found evidence for large percentages of O and Fe existing in the form of solids, so the residuals could be due to features associated with this dust. This may also explain the fact that our O III column densities are always higher than O II if it is overestimating O III to make up for the lack of solids at 23 Å. At the oxygen K-edge though, Gattuz et al. (2016) find that using more recent atomic cross-sections than those used in Pinto et al. (2010) can provide a good fit in the 21–24 Å region. We have tested the effects of adding dust to the model and found that it makes only a very minor difference in the determination of disc parameters as shown from the results in Table 3. So, while a more complete model of all three phases of the ISM may be able to fit the finer features of the RGS data more effectively, not including dust leads to only a very small bias in the results of broad-band spectral fitting.

From our best fits, we find a wide range of hydrogen column densities, some of which differ greatly from those presented in previous surveys. The best agreement seems to come from the results of Willingale et al. (2013) with GRO J1655−40, GX 339−4 and Swift J1753.5−0127 having approximately the same column density. Our GS 1354−64 estimate sits between the Kalberla et al. (2005) and Willingale et al. (2013) results. The XTE J1720−318 result is more than two times larger than all three 21 cm maps, but is in agreement with a value found in Cadolla Bel et al. (2004). In general, there seems to be a tendency for finding higher N_H values from soft X-ray fitting compared to those from the 21 cm maps, in agreement with previous work. X-ray absorption spectroscopy cannot distinguish between absorption due to H, He I and He II. Differences in the abundance of He (relative to H) compared to that assumed in the ISM model (N_H/N_He = 0.1) may explain slight differences in the N_H values inferred from X-ray spectroscopy and from 21 cm maps.

We also compare three of our results with those from Gatuzz et al. (2016), who also used the ISM model for their calculations. We find a slightly smaller N_H for GRO J1655−40, but a larger value for GX 339−4 and Swift J1753.5−0127, with Swift J1753.5−0127 having a significant discrepancy (more than two orders of magnitude). Gatuzz et al. (2016) claim the choice of continuum model can produce different column densities despite similar fit statistics. This could explain our disagreements as they used a broken power law to model the continuum. We tested this by performing our own ISM fits and found results mostly in agreement with them, except in the case of Swift J1753.5−0127, with the broken power law giving slightly better fit statistics. The value for Swift J1753.5−0127 presented in Gatuzz et al. (2016) is inconsistent with all other estimates of this source (their value is more than 100 times lower than those from the 21 cm maps). This value is more than two times larger than those from the 21 cm maps. This in turn means the relative abundances of the metals are two orders of magnitude higher than typical (e.g. Wilms et al. 2000), and would require a H column density towards Swift J1753.5−0127 lower than that through the Lockman Hole (Lockman, Jahoda & McCammon 1986). We therefore remain confident in our results as we believe they represent a more realistic situation.

Given the level of disagreement between the results from our model and those from the literature, it is clear that the value of N_H does need to be treated with care, and that estimates of N_H derived from spectral analysis of RGS data can be very sensitive to the choice of continuum. However, the best way to deal with these model dependencies is still unclear.

21 cm maps can act only as a proxy for X-ray absorption. Soft X-ray absorption on BH XRBs spectra has strong contributions from molecular H, atomic and ionized He, and from metals in the ISM. The 21 cm maps can act only as a proxy for X-ray absorption.

5 DISCUSSION

Figure 2. The best-fitting emission model parameters as a function of the assumed N_HI for different true values of N_HI based on fitting simulated EPIC data. The results from the hard state are found in the left column, with the soft state on the right. The N_HI = 0.3 × 10^22, 0.9 × 10^22, and 1.5 × 10^22 cm^-2 results are shown in the red, blue and green data points, respectively. The dashed line on each plot represents the true parameter value.
Figure 3. Contour plots from the MCMC analysis of a simulated hard state EPIC broad-band spectrum fitted with a model with free parameters: $N_H$, $\Gamma$, $f_{\text{scat}}$, $\dot{m}$ and $f_{\text{col}}$. Contours represent $1\sigma$, $2\sigma$ and $3\sigma$ confidence levels. The true parameter values are: $N_H = 0.3 \times 10^{22}$ cm$^{-2}$, $\Gamma = 1.7$, $f_{\text{scat}} = 0.5$, $\dot{m} = 0.1 \times 10^{18}$ g s$^{-1}$ and $f_{\text{col}} = 1.5$.

Table 3. Results of tests on the effect of including dust in the ISM model. An EPIC spectrum is simulated with a gas+dust model, and fitted with a gas+dust model (left) and a gas-only model (right). Here, $\dot{m}$ is in units of $10^{17}$ g s$^{-1}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ISMabs*TBvarabs</th>
<th>ISMabs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$</td>
<td>1.699 ± 0.001</td>
<td>1.700 ± 0.001</td>
</tr>
<tr>
<td>$f_{\text{scat}}$</td>
<td>0.501 ± 0.001</td>
<td>0.497 ± 0.001</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>0.998 ± 0.002</td>
<td>1.012 ± 0.004</td>
</tr>
<tr>
<td>$f_{\text{col}}$</td>
<td>1.504 ± 0.001</td>
<td>1.490 ± 0.007</td>
</tr>
<tr>
<td>$\chi^2_{\text{red}}$(dof)</td>
<td>1.04(146)</td>
<td>1.11(146)</td>
</tr>
</tbody>
</table>

ISM. There is also the possibility of small-scale variations in the ISM that are not resolved by most 21 cm maps, or absorption local to the source, perhaps even influenced by the source, such as an accretion disc wind. None of these will show up in 21 cm data and have to be assumed unless explicitly estimated from the soft X-ray data. Therefore, if the differences that we are seeing are due to a combination of these additional factors then this at least justifies the use of the soft X-ray grating data to provide more specific column density estimates for a given source.

From the analysis of the GX 339−4 observations, we have been able to track changes in absorption features over $\sim 13$ yr. The fitted $N_H$ values can be found in Table 1. In all cases, we find an acceptable fit and a good agreement over all observations with a spread of $N_H = (0.536 - 0.589) \times 10^{22}$ cm$^{-2}$. These are consistent with the value of $5.1 \pm 0.4 \times 10^{22}$ cm$^{-2}$ found in Pinto et al. (2013), but higher than the $4.1 \pm 0.5 \times 10^{22}$ cm$^{-2}$ in Gatuzz et al. (2016). In addition, we find no correlation between $N_H$ and spectral state as presented in Cabanac et al. (2009).

We have also attempted to estimate the affect on using older models and incorrect column densities on the spectral fitting of EPIC data. We find that using a model such as $\text{wabs}$ instead of the more detailed ISMabs can have a systematic effect on disc parameters. For all values of true $N_H$, we see that using $\text{wabs}$ produces a stronger absorption component, which will simply be due to the differences in the cross-section data. Beyond that, we can see some clear relations between the level of absorption and the true values of the disc parameters. In the hard state, getting the $N_H$ value wrong affects all four free parameters. The spectral index of the power law increases with the tested $N_H$, with values approaching 2 for the worst fits. The scattering fraction decreases, ultimately producing results much more characteristic of the soft state than the hard. The largest impact though is on the blackbody component, with both $\dot{m}$ and $f_{\text{col}}$ rapidly entering unrealistic values. The picture is similar in the soft state only with $f_{\text{scat}}$ trending in the opposite direction with higher $N_H$ leading to a higher number of photons scattered into the power law. The use of MCMC analysis illustrates the level of covariance $N_H$ has with the four spectral parameters. Fig. 3 shows contour plots for each of the free parameters when fitting the simulated data. $N_H$ is very strongly correlated with $f_{\text{scat}}$ and $\dot{m}$, with an overestimation of $N_H$ leading to an underestimation of $f_{\text{scat}}$ and a simultaneous overestimation of $\dot{m}$. Allowing the fitted $N_H$ values to go free has a much less significant effect on the disc parameters with, in most cases, the fitted values being very close...
to those simulated. They do require though a much smaller fitted hydrogen column density, with an approximately 30 per cent drop in each case.

In general, we can see that for any spectral fitting in which there is no independent assessment of the amount of absorption present it is better to allow the hydrogen column density as a free parameter in all cases. Not doing so systematically changes the inferred temperature of the disc for even small inaccuracies in the $N_H$ value. This will ultimately lead to a bias on estimates of basic system parameters such as the BH mass or disc inner radius.

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**SUPPORTING INFORMATION**

Supplementary data are available at MNRAS online.
aje_Appendix.pdf

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