

A broad absorption feature in the X-ray spectrum of the isolated neutron star RBS1223 (1RXS J130848.6+212708)[★]

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Abstract. X-ray spectra of the isolated neutron star RBS1223 obtained with the instruments on board XMM-Newton in December 2001 and January 2003 show deviations from a Planckian energy distribution at energies below 500 eV. The spectra are well fit when a broad, Gaussian-shaped absorption line with $\sigma = 100$ eV and centered at an energy of 300 eV is added to an absorbed blackbody model. The resulting equivalent width of the line is ~ 150 eV. However, the spectral resolution at these low energies of the EPIC detectors and the lower statistical quality and restricted energy band of the RGS instruments are not sufficient to exclude even broader lines at energies down to 100 eV or several unresolved lines. The most likely interpretation of the absorption feature is a cyclotron absorption line produced by protons in the magnetic field of the neutron star. In this picture line energies of 100–300 eV yield a magnetic field strength of $2\text{--}6 \times 10^3$ G for a neutron star with canonical mass and radius. Folding light curves from different energy bands at a period of 10.31 s, which implies a double peaked pulse profile, shows different hardness ratios for the two peaks. This confirms that the true spin period of RBS1223 is twice as long as originally thought and suggests variations in cyclotron absorption with pulse phase. We also propose that changes in photo-electric absorption seen in phase resolved spectra of RX J0720.4–3125 by Cropper et al. (2001), when formally fit with an absorbed blackbody model, are caused instead by cyclotron absorption varying with pulse phase.

Key words. stars: individual: RBS1223 = 1RXS J130848.6+212708 – stars: neutron – stars: magnetic fields – X-rays: stars

1. Introduction

The soft X-ray source 1RXS J130848.6+212708 was discovered in the ROSAT all-sky survey data and further studied as part of the ROSAT Bright Survey program (RBS, source number 1223) to optically identify the brightest ~ 2000 high-galactic latitude sources (Schwope et al. 2000). Based on similarities to the two best known cases RX J1856.4–3754 and RX J0720.4–3125 and the lack of an optical counterpart brighter than $B \sim 26^m$, Schwope et al. (1999) proposed 1RXS J130848.6+212708 = RBS1223 as isolated neutron star (INS). Using the Chandra observatory Hambaryan et al. (2002) observed RBS1223 on June 24, 2000 with the ACIS instrument and discovered pulsations in the X-ray flux, initially indicating a neutron star spin period of 5.16 s. A probable optical counterpart in the 90% Chandra error circle was reported by Kaplan et al. (2002a) using a very deep observation from the Hubble Space Telescope. The optical brightness of $m_{50\text{CCD}} = 28.6^m$ yields an X-ray to optical flux ratio of $\log(f_x/f_{\text{opt}}) = 4.9$.

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The optical flux is a factor of about 5 above the extrapolation of the blackbody fit to the X-ray spectrum, similar as observed for RX J1856.4–3754 (e.g. Burwitz et al. 2003) and RX J0720.4–3125 (Pavlov et al. 2002).

This confirms RBS1223 as member of a group of X-ray dim INSs which share similar properties (for a recent review see Haberl 2003): soft blackbody-like X-ray spectrum, radio quiet and no known association with a supernova remnant. Four objects are X-ray pulsars with neutron star spin periods in the range 8.39 to 22.7 s (the XMM-Newton observations of RBS1223 revealed a peak in the power spectrum at half the frequency of the main peak which suggests that the genuine spin period is 10.31 s with a double peaked profile, Haberl 2003). All available spectra obtained by the ROSAT PSPC were consistent with Planckian energy distributions with blackbody temperatures kT in the range 40–100 eV and little attenuation by interstellar absorption. More recent observations of the two brightest objects RX J1856.4–3754 (Burwitz et al. 2001; Burwitz et al. 2003) and RX J0720.4–3125 (Paerels et al. 2001; Pavlov et al. 2002) were performed using the low energy transmission grating (LETG) aboard Chandra and the reflection grating spectrometers (RGS) of XMM-Newton. Also at high spectral resolution both sources show featureless spectra

Table 1. XMM-Newton observations of RBS1223.

Time (UT)		XMM	Read-out	Count rate	Exp.
Start	End	Detector	Mode	[s ⁻¹]	[ks]
2001 Dec. 31, Satellite Revolution 377 (AO1)					
03:08	08:41	MOS1/2	Full Frame	0.49/0.52	19.8
03:32	08:42	pn	Small Window	2.47	19.0
03:02	08:42	RGS1/2	Spectro+Q	0.09/0.07	20.4
2003 Jan. 1, Satellite Revolution 561 (CAL)					
06:13	14:14	MOS1/2	Large Window	0.47/0.48	28.7
06:36	14:14	pn	Full Frame	2.39	27.0
06:12	14:15	RGS1/2	Spectro+Q	0.10/0.08	28.9

Mean count rates are given for the energy band used for the spectral analysis (EPIC: 0.13–1.3 keV, RGS: 0.32–0.90 keV). The thin filter was used in all EPIC cameras during both observations.

which can best be modeled by a Planckian spectrum with kT of ~ 63 eV and ~ 86 eV, respectively.

The pulsars among the X-ray dim INSs may allow an estimate of the strength of their magnetic field if their long-term spin period increase can be interpreted in terms of dipolar losses. For the pulsar RX J0720.4–3125 Kaplan et al. (2002b) derived an upper limit for the period derivative of $3.6 \times 10^{-13} \text{ s s}^{-1}$ from the analysis of ROSAT, SAX and Chandra data and including first XMM-Newton data, Zane et al. (2002) determined possible values between $3\text{--}6 \times 10^{-14} \text{ s s}^{-1}$. This implies that the magnetic field strength of RX J0720.4–3125 could be as high as a few 10^{13} G. For such magnetic field strengths an absorption feature at the proton cyclotron resonance energy, $E_{\text{cp}} = 63g_{\text{r}}(B/10^{13} \text{ G}) \text{ eV}$ ($g_{\text{r}} = (1 - 2GM/c^2R)^{1/2}$ with M and R the neutron star mass and radius, respectively), may become detectable (Zane et al. 2001; Zavlin & Pavlov 2002) with detectors sensitive at soft X-rays down to 100 eV.

In this letter we present the results from a spectral analysis of two XMM-Newton observations of RBS1223. The spectra show deviations from a Planckian energy distribution which can best be modeled by a broad absorption feature at low energies. We discuss this feature as most likely being caused by proton cyclotron resonance absorption.

2. XMM-Newton observations

XMM-Newton (Jansen et al. 2001) observed RBS1223 on two occasions; in the guest observer program (AO1, PI: Schwöpe) and for calibration purposes at the beginning of the year 2003. Here we utilize the data collected with the European Photon Imaging Cameras (EPICs) and the Reflection Grating Spectrometers (RGSs, den Herder et al. 2001) for a spectral analysis. Two EPIC cameras are based on MOS (EPIC-MOS1 and -MOS2, Turner et al. 2001) and one on pn (EPIC-pn, Strüder et al. 2001) CCD detectors and are mounted behind the three X-ray multi-mirror systems. The details of the XMM observations are summarized in Table 1.

3. X-ray spectra

The data from the EPIC instruments were processed using SAS5.4.1 to produce event files for pn, MOS1 and MOS2. RGS spectra and response files were created using `rgsproc` of SAS5.4.1 with standard settings. The EPIC spectra were extracted from circular regions with $30''$ radius around the target position and nearby background regions using single-pixel events (pattern 0) from pn and pattern 0–12 events from MOS data. Detector response matrix files were used as available from the EPIC-pn calibration group in February 2003 (version 6.5 which will be implemented in the next SAS release after SAS5.4.1) and were created for MOS using the `arfgen` and `rmfgen` tasks of SAS5.4.1. MOS spectra from recent observations suffer from a considerable change in the low energy re-distribution which is not calibrated yet. Therefore, we use MOS spectra from the first observation in Dec. 2001, only. The pn spectra from the two observations, obtained in different read-out modes, are in agreement within the current calibration uncertainties and also are consistent with the MOS spectra from the Dec. 2001 observation.

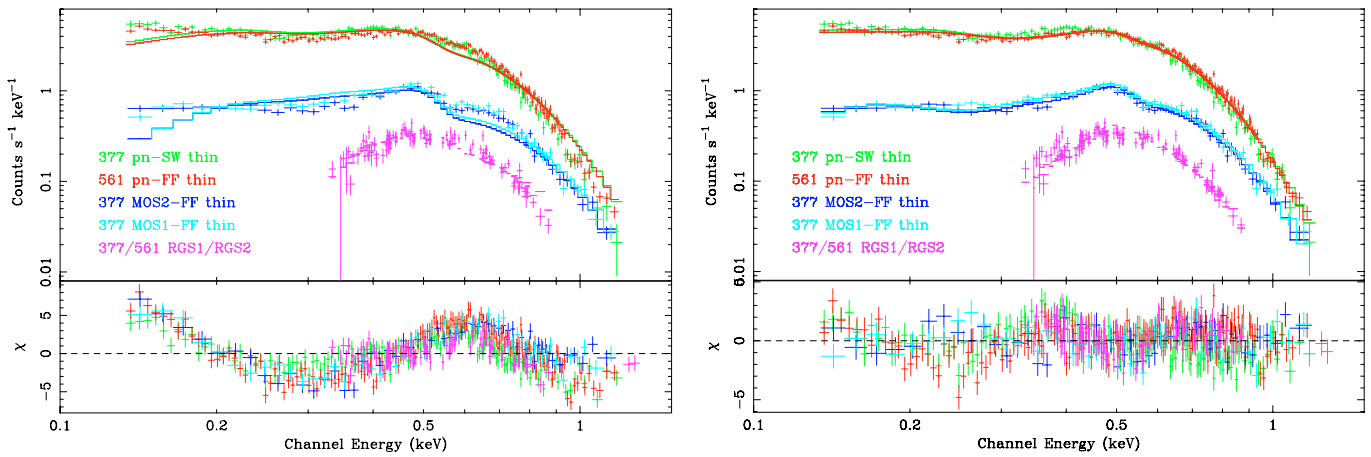
The spectra were simultaneously fitted with various models, all including photo-electric absorption with element abundances from Anders & Grevesse (1989) and cross-sections from Balucinska-Church & McCammon (1992) and Yan et al. (1998) using XSPEC version 11.2.0. To account for cross-calibration uncertainties between the instruments and the fact that the pn spectra were not corrected for point spread function losses (the SAS5.4.1 task `arfgen` is not compatible to the response files we used here) the relative normalization between the instruments/observations were allowed to vary individually. The pn fluxes were corrected manually by a factor 1.2 to correct for the PSF loss according to the XMM-Newton users handbook. In addition uncertainties in the low-energy re-distribution were accounted for by allowing individual column density values for pn, MOS1 and MOS2. The RGS spectra show relatively large differences in continuum parameters which were then fit for each spectrum separately.

As first model an absorbed blackbody was used, however, the combined fit to the XMM spectra of RBS1223 is not acceptable with χ^2_{r} of 5.2 for 639 degrees of freedom (d.o.f.). The spectra together with the fit are shown in Fig. 1 and the fit parameters summarized in Table 2. Because of the bad fit we do not give errors and fluxes for this model. In particular, the EPIC spectra with best statistical quality yield high χ^2 values which we report for each instrument separately in Table 2. Since the combined fit is dominated by the high statistics of the EPIC-pn spectra we allowed all model parameters for the RGS spectra to be fit freely, i.e. the RGS fit is completely independent from the pn fit. This allows to judge if the RGS spectra on their own can be well fit by a blackbody model.

We also tried non-magnetic neutron star atmosphere models (e.g. Gänsicke et al. 2002; Zavlin & Pavlov 2002). Iron and solar mixture atmospheres cause too many absorption features and deviations from a blackbody model in particular at energies between 0.5 and 1.0 keV which are not seen in the measured spectra. On the other hand the spectrum of a pure hydrogen model is similar in shape to that of a blackbody and

Table 2. Spectral fit results.

Obs.-Instrument	Model A: phabs*(bbody)			Model B: phabs*(bbody+Gaussian)					
	kT [eV]	N_{H} [10^{20} cm^{-2}]	$\chi^2/\text{d.o.f.}$ per instr.	kT [eV]	N_{H} [10^{20} cm^{-2}]	E_{line} [eV]	EQW [eV]	$\chi^2/\text{d.o.f.}$ per instr.	Flux ⁽¹⁾ [$\text{erg cm}^{-2} \text{ s}^{-1}$]
AO1-pn	95.1	7.1	2138/309	85.8 ± 0.5	4.1 ± 0.1	290 ± 5	-148	589/307	3.65×10^{-12}
CAL-pn	=1 ⁽²⁾	=1		=1	=1	=1	-148		3.44×10^{-12}
AO1-MOS1	=1	4.9	845/109	=1	2.9 ± 0.2	302 ± 2	-159	156/108	3.33×10^{-12}
AO1-MOS2	=1	5.3		=1	3.2 ± 0.2	=3	-159		3.62×10^{-12}
AO1-RGS1	103	7.1	349/221	82.2 ± 2.4	5.0 ± 0.6	=1	-	318/221	2.62×10^{-12}
AO1-RGS2	109	=5		85.2 ± 2.6	=5	=1	-		2.50×10^{-12}
CAL-RGS1	112	=5		87.8 ± 1.6	=5	=1	-		2.66×10^{-12}
CAL-RGS2	108	=5		87.6 ± 1.5	=5	=1	-		2.62×10^{-12}
ACIS	81.1	19	253/38	87.8 ± 1.0	<1.6	290fixed	-	91/38	3.34×10^{-12}

⁽¹⁾ Observed flux 0.1–2.4 keV; ⁽²⁾ “=n” denotes fit parameter is linked with parameter in line n.**Fig. 1.** Blackbody model fits to EPIC-pn (upper pair), EPIC-MOS (middle pair) and RGS spectra of RBS1223. The four RGS spectra were combined in the plot for clarity. While the pure blackbody model fit (left) is unacceptable, including a broad Gaussian absorption line at ~ 300 eV (right) can reproduce the data. The residuals (bottom panels) show consistent behavior for all instruments.

does not fit the data either. It also results in a much lower effective temperature of about 30 eV which would predict a far too high optical flux (see Pavlov et al. 1996). Using the models of Gänsicke et al. (2002) χ^2_{r} values of 12, 29 and 12 (for the combined EPIC spectra) are obtained for Fe, solar mixture and H atmospheres, respectively. A two-temperature blackbody fit results in $\chi^2_{\text{r}} = 6.6$ with $kT_1 = 33$ eV and $kT_2 = 94$ eV. The strong residuals at energies below 500 eV remain. Such residuals are not seen in fits to the spectra of RX J1856.4–3754 with typical reduced χ^2_{r} values of 1.5 using the same version of spectral response files, clearly excluding calibration problems as origin.

An acceptable fit was found when including a broad absorption line in the model. Because of the low line energy and the large line width the low resolution of the EPIC detectors and the limited band pass of the RGS instruments do not allow to independently vary energy and width of the line. A broad line centered at the lowest energies reachable by the detectors (~ 120 eV) leaks only partially into the sensitive energy band and can therefore not be distinguished from a somewhat narrower line at somewhat higher energy. All we can say is that the absorption feature is extended up to ~ 500 eV. Models with an absorption line at 300 eV with $\sigma = 100$ eV or a line at 200 eV

with $\sigma = 150$ eV can not be distinguished. Also multiple lines at e.g. 150 eV and 300 eV which are correspondingly narrower can not be excluded. However, too broad lines are probably unrealistic (see e.g. Zane et al. 2001, if interpreted as cyclotron resonance) and we therefore use in our fits a single absorption line of Gaussian shape with fixed $\sigma = 100$ eV. This yields a best fit with $\chi^2_{\text{r}} = 1.67$ for 636 d.o.f. (Fig. 1) with parameters listed in Table 2. The line energy was allowed to be fit individually for the two EPIC instruments but is consistent within the errors. Because the sensitive energy band of the RGS instruments covers the broad line only partially, we forced all line parameters to be the same in the fit for the pn and all RGS spectra simultaneously. For the same reason we do not give values for the line equivalent width (EQW) for the RGS spectra. The χ^2 obtained from the RGS spectra for this model is reduced by 31 (without adding additional d.o.f.s) as compared to the blackbody model which may be accepted for RGS if treated by its own.

We re-analyzed the ACIS-S spectrum of RBS1223, published by Hambaryan et al. (2002), using the re-processed data available in the Chandra archive and new calibration which allows a spectral analysis down to 350 eV. We fit blackbody with and without absorption line to the spectrum, with all

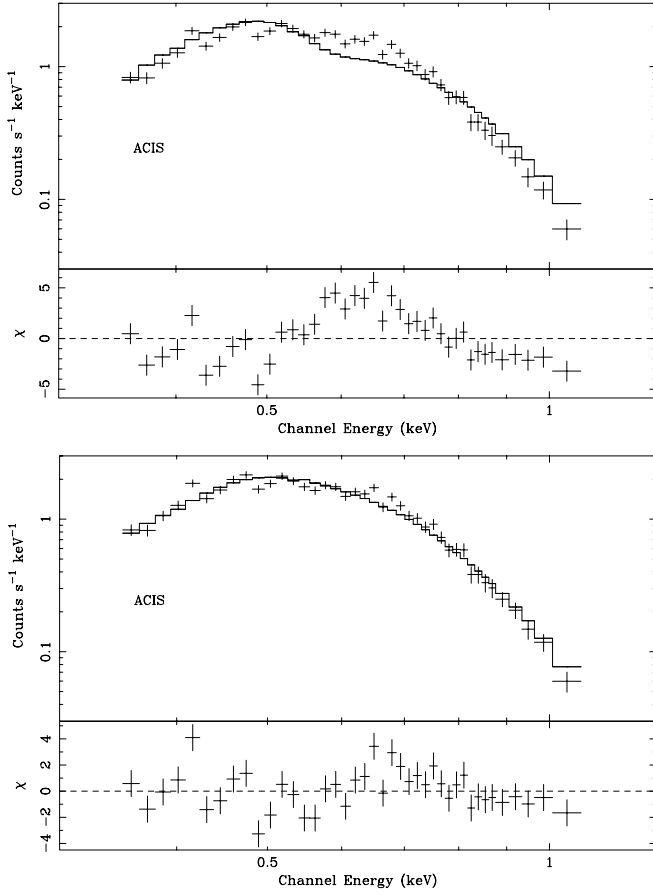


Fig. 2. Blackbody model fits with (bottom) and without absorption line to the ACIS-S spectrum of RBS1223.

line parameters fixed at the values derived from the fit to the XMM-Newton spectra. The fits are shown in Fig. 2 and the model parameters reported in Table 2. The results are in good agreement to those obtained from the XMM-Newton data.

4. X-ray pulsations

To investigate spectral changes with pulse phase, light curves in the energy bands 0.12–0.5 and 0.5–1.0 keV were folded with a pulse period of 10.31 s. This long period with double peaked profile is suggested by the presence of a second peak in the power spectrum (Haberl 2003). The different relative strength of the two peaks in the two energy bands and the related significant difference in hardness ratio (Fig. 3) strongly supports a 10.31 s spin period of RBS1223, twice as long as originally thought.

5. Discussion

Spectral analysis of the INS RBS1223 using data obtained by the X-ray instruments aboard XMM-Newton revealed significant deviations from a Planckian energy distribution at energies below ~ 500 eV. Also, non-magnetic atmosphere models yield unacceptable fits. We find that a model including a broad absorption line on top of the blackbody continuum can reproduce the observed spectra. For a Gaussian line with

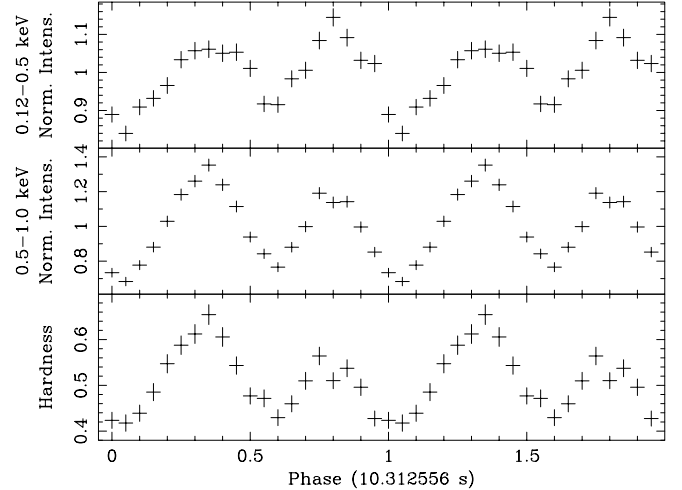


Fig. 3. Pulse profile of RBS1223 in the 0.12–0.5 keV (soft) and 0.5–1.0 keV (hard) energy bands, together with the ratio hard/soft, obtained from the EPIC-pn data of the Jan. 2003 observation.

fixed $\sigma = 100$ eV we derive an energy of the line of ~ 300 eV and an equivalent width of ~ 150 eV. However, the spectral resolution of the EPIC instruments at these energies and the restricted energy coverage of the RGS are not sufficient to exclude line energies as low as 100 eV or multiple lines which are unresolved.

Cyclotron resonance absorption features in the 0.1–1.0 keV band are expected in spectra from magnetized neutron stars with field strengths in the range of 10^{10} – 10^{11} G or 2×10^{13} – 2×10^{14} G if caused by electrons or protons, respectively (see e.g. Zane et al. 2001; Zavlin & Pavlov 2002). A strong magnetic field for RBS1223 of $\sim 2 \times 10^{14}$ G was first derived by Hambaryan et al. (2002) from a first estimate of the spin period derivative based on a ROSAT and a Chandra observation. The first of the two XMM-Newton observations described here, however, put this into question (for preliminary results see Haberl 2003) and placed only an upper limit of 10^{14} G. A detailed temporal analysis of the two XMM-Newton observations and a re-analysis of the Chandra data will be published in an accompanying paper (Hambaryan et al. in preparation).

Recently, several radio pulsars with magnetic field strength of a few 10^{13} G with similar long spin period as RXJ0720.4–3125 and RBS1223 were discovered (Camilo et al. 2000; Morris et al. 2002). If one assumes a comparable field strength for RBS1223 which may be justified if the ROSAT discovered radio-quiet INSs are cases where the radio beam does not cross the Earth (Kaplan et al. 2002b; Motch et al. 2003), but are otherwise similar objects, one would favor cyclotron resonance absorption due to protons to be responsible for the features seen in the spectra of RBS1223. Then our measured line energies between 100 and 300 eV translate into magnetic field strengths of 2 – 6×10^{13} G for a neutron star with canonical mass ($1.4 M_{\odot}$) and radius (10 km).

By folding the EPIC-pn data of RBS1223 in two energy bands with a period of 10.31 s we see hardness ratio changes with pulse phase. The two pulses show different hardness which may be explained by variations in cyclotron absorption

between two magnetic poles. Detailed phase resolved spectroscopy which exceeds the scope of this letter, is in progress and will be reported elsewhere.

Variations in the hardness ratio with pulse phase were also reported from RX J0720.4–3125. Formal fits using a blackbody spectrum attenuated by photo-electric absorption performed by Cropper et al. (2001) to the pulse-phase resolved EPIC-pn spectra around hardness maximum and minimum yielded changes in column density, but little variations in blackbody temperature. This could be explained in terms of energy-dependent beaming effects with softer photons more strongly beamed than harder photons. From their polar cap modeling of the spin pulse profile the authors conclude that the derived geometries are at best marginally compatible with surface temperature variation but more satisfactory explained by an accretion model. However, the possibility of accretion of interstellar matter is now most likely excluded by the measured high proper motion of RX J0720.4–3125 (Motch et al. 2003). On the other hand, the variations with pulse phase could be naturally explained by cyclotron absorption, because we may view surface areas with different magnetic field strength and orientation during the rotation of the neutron star. A cyclotron absorption line at the low energy end of the sensitive energy band of the EPIC instruments would cause deviations from a Planckian shape at these energies which, so far, were not recognized due to lack of statistics and/or energy resolution and preliminary calibration of the new generation instruments.

Zane et al. (2001) calculate spectra emerging from ultra-magnetized neutron stars covered by non-degenerate, pure hydrogen plasma. They explored ranges in magnetic field strength from 10^{13} G to 10^{15} G and in luminosity from 10^{34} erg s $^{-1}$ to 10^{36} erg s $^{-1}$. Although the luminosity of RBS1223 may only be around 10^{31-32} erg s $^{-1}$ their results for the line EQW shows little dependence on luminosity and may be compared to the value of 150 eV we find for RBS1223. Their predictions for cyclotron line widths and equivalent width and the overall blackbody-like continuum for the case of a dipolar magnetic field (which broadens the line due to B field variations in magnitude and direction along the neutron star surface) are consistent with our results for RBS1223. This suggests, that at least for RBS1223 and probably also RX J0720.4–3125 a H atmosphere exists on these neutron stars and argues against a condensed matter surface as it was proposed to explain the combined spectral energy distribution in the optical and X-ray bands (Burwitz et al. 2003; Zane et al. 2003). However, an optically thick H atmosphere produces too much optical flux (Pavlov et al. 1996), a problem which may be reduced by thin atmosphere models as was applied by Motch et al. (2003) to RX J0720.4–3125.

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