Narrow absorption features in the co-added XMM-Newton RGS spectra of isolated Neutron Stars.

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ABSTRACT
We co-added the available XMM-Newton RGS spectra for each of the isolated X-ray pulsars RX J0720.4−3125, RX J1308.6+2127 (RBS1223), RX J1605.3+3249 and RX J1856.4−3754 (four members of the “Magnificent Seven”) and the “Three Musketeers” Geminga, PSR B0656+14 and PSR B1055-52. We confirm the detection of a narrow absorption feature at 0.57 keV in the co-added RGS spectra of RX J0720.4−3125 and RX J1605.3+3249 (including most recent observations). In addition we found similar absorption features in the spectra of RX J1308.6+2127 (at 0.53 keV) and maybe PSR B1055-52 (at 0.56 keV). The absorption feature in the spectra of RX J1308.6+2127 is broader than the feature e.g. in RX J0720.4−3125. The narrow absorption features are detected with 2σ to 5.5σ significance.

Although very bright and frequently observed, there are no absorption features visible in the spectra of RX J1856.4−3754 and PSR B0656+14, while the co-added XMM-Newton RGS spectrum of Geminga has not enough counts to detect such a feature.

We discuss a possible origin of these absorption features as lines caused by the presence of highly ionised oxygen (in particular OVII and/or OVI at 0.57 keV) in the interstellar medium and absorption in the neutron star atmosphere, namely the absorption features at 0.57 keV as gravitational redshifted \( g_r = 1.17 \) OVIII.

Key words: stars: neutron – pulsars: individual: RX J0720.4−3125 – pulsars: individual: RX J1308.6+2127 – pulsars: individual: RX J1605.3+3249 – pulsars: individual: RX J1856.4−3754 – pulsars: individual: Geminga – pulsars: individual: PSR B0656+14 – pulsars: individual: PSR B1055-52

1 INTRODUCTION
Neutron stars (NSs) give us the opportunity to study matter under extreme conditions, such as high densities \( \rho \approx 10^{15} \text{ g/cm}^3 \), strong magnetic fields \( B \approx 10^{13} \text{ G} \) and high temperatures \( T \approx 10^6 \text{ K} \). Such conditions cannot be generated in laboratories and theoretical predictions need observational input to understand satisfactorily the behaviour of matter under these conditions, in particular for the interior of NSs. One main goal of NS astrophysics is to constrain the Equation of State (EoS) at supra-nuclear densities that would give us fundamental insights into various fields of physics, therefore suitable targets have to be found. Most of the \( \approx 2000 \) known NSs (Manchester et al. 2005) are radio pulsars, among them nine double NSs were found so far (see Stairs 2006 for a review) that enable us to determine their masses with high accuracy. However, it is not possible to infer the radius or compactness of these objects. In principle, the radius could be measured from the luminosity of cooling (hence, blackbody radiation) NSs, if the distance and temperature are known, using the modified Stefan-Boltzmann law. If spectral lines could be detected as well, they deliver an estimate for the compactness of the particular NS from measuring the gravitational redshift \( g_r \).

\[ g_r = \frac{1}{\sqrt{1 - r_s/R_{NS}}} \]

Here, \( g_r \) denotes the Schwarzschild radius.
On the other hand, spectral features can be caused by the interstellar medium (ISM): The Sun is located in a 1MK hot cavity of about 300 pc radius, the so-called Local Bubble (Lallement et al. 2003) that was formed by multiple supernovae in the last few Myrs (Breitschwerdt & de Avillez 2006; Breitschwerdt et al. 2009). The Local Bubble (LB) is filled with a thin hot plasma including highly ionized mid Z-elements (in particular He-like oxygen). The exact temperature of the LB is currently under debate (Kuntz 2009; Shelton 2009), but this environment likely causes absorption features in the soft X-rays. Thus, narrow absorption features in the spectra of isolated X-ray sources can be caused by the ISM and/or by intrinsic processes.

We selected those isolated NSs for our work that are bright in the X-rays, have simple spectral properties and that are observed deep enough with XMM-Newton RGS, hence four members of the “Magnificent Seven” (RX J0720.4−3125, RX J1308.6+2127², RX J1605.3+3249 and RX J1856.4−3754) and all members of the “Three Musketeers” (Geminga, PSR B0656+14 and PSR B1055-52). We co-added the high resolution RGS spectra of these targets and searched for narrow, maybe redshifted, absorption lines.

1.1 The “Magnificent Seven”

During the ROSAT All Sky Survey, seven soft X-ray sources, the so called “Magnificent Seven” (hereafter M7), were discovered that are suitable targets for such investigations. The M7 exhibit soft X-ray spectra that are best modelled with blackbody radiation (kT eff ≈ 40–110 eV) with broad absorption features in some cases. These absorption features are interpreted as proton-cyclotron resonances or atomic transitions of bound species in a strong magnetic field at B ≈ 10¹³ G. No radio emission could be detected from the M7 (see e.g. Kondratiev et al. 2009), but they exhibit X-ray pulsations with periods between 3 s and 12 s. All M7 are isolated, i.e. they are not associated with a supernova remnant, do not belong to a binary system and no sub-stellar companions are found so far (Posselt et al. 2009). The kinematic and characteristic age estimates yield values of 0.3–3 Myrs (Haberl 2007; Tetzlaff et al. 2010). The two brightest members, RX J1856.4−3754 and RX J0720.4−3125, have known trigonometric parallaxes (Walter et al. 2010; Kaplan et al. 2009, 2007, yielding distances of 280+210−85 pc.

² RBS1223
³ For RX J0720.4−3125, Eisenbeiss (2011) obtains a distance of 280+210−85 pc.

et al. 2005 for a review). The magnetic fields of the 3M (B ≈ 10¹¹ G) are a factor of ten weaker than those of the M7, but the 3M are younger by trend (a few 10⁷ yrs). Geminga (discovered by Bignami et al. 1983) and PSR B0656+14 (discovered by Cordova et al. 1989) have distances derived from trigonometric parallaxes (Caraveo et al. 1996; Brisken et al. 2003; Walter 2005) ranging from 150 pc to 300 pc, while the distance of PSR B1055-52 (750 pc) is estimated from dispersion measurements (Kramer et al. 2003). Geminga and PSR B1055-52 also exhibit pulsations in gamma-rays (Fierro 1993; Bertsch et al. 1992).

2 XMM-NEWTON OBSERVATIONS

All XMM-NEWTON Reflection Grating Spectrometer (RGS, den Herder et al. 2001) observations have been analysed and reprocessed with the standard XMM-NEWTON Science Analysis System (SAS) version 10.0 using the rgsproc task. We checked the background of each observation individually and created Good Time Intervall (GTI) files that filter out those times with count rates above 0.25 or 0.1 cts/s (depending on the source and background behaviour) determined for CCD number nine of RGS1 and ran rgsproc again for GTI filtering. The photons for the spectra were obtained from the default RGS extraction regions and we co-added the spectra using rgscombine (that also produces co-added background spectra and the corresponding response matrices) allowing to investigate the total average spectrum with high energy resolution. The RGS2 detector does not provide spectral information in the required energy band (due to the failure of chip four) around 0.57 keV, thus could not be used. The co-added spectra are fitted and investigated using Xspec 12. We explain the data handling and fitting and fit results of the individual sources in the following sections.

2.1 RX J0720.4−3125

In contrast to the other M7, RX J0720.4−3125 shows significant spectral and temporal variations on time scales of years that might be caused by a glitch (van Kerkwijk et al. 2007, see also Kaplan & van Kerkwijk 2005) or free precession (Hohle et al. 2009, 2010; Haberl 2007; Haberl et al. 2006; de Vries et al. 2004). Due to this peculiarity, RX J0720.4−3125 is one of the best investigated members of the M7. Since more than ten years RX J0720.4−3125 is frequently observed with XMM-NEWTON and Chandra.

After co-adding all available XMM-NEWTON RGS spectra of RX J0720.4−3125, Hambaryan et al. (2009) reported the detection of a narrow absorption feature at 0.57 keV. This feature was interpreted as the Kα absorption line of highly ionised oxygen: either OVI and/or OVII at rest, or OVI (in this case Lyα/Kα) with a gravitational redshift of γ = 1.16, see Hambaryan et al. (2009). In Hambaryan et al. (2009) it is argued that this absorption feature, if oxygen, may originate from the ambient medium of the NS, maybe from a circumstellar disk surrounding RX J0720.4−3125. The presence of such a disk may account partly for some of the peculiarities of RX J0720.4−3125 (Hambaryan et al. 2009).

Since the work of Hambaryan et al. (2009), we performed four further XMM-NEWTON observations. We re-investigated
Table 1. The XMM-Newton RGS1 observations of RX J0720.4−3125 in chronological order. We list the exposure times and the net counts after the data passed the GTI filters.

| Obs. ID          | date        | counts | eff. exposure |
|-----------------|-------------|--------|---------------|
|                 |             | 0.35-1.0 keV | [ks]         |
| 0124100101      | 2000 May 13 | 11480 | 42.36         |
| 0132520301      | 2000 Nov 21 | 7878  | 30.24         |
| 0156690201      | 2002 Nov 6  | 7518  | 29.61         |
| 0156604001      | 2002 Nov 8  | 7796  | 31.22         |
| 0158360201      | 2003 May 2  | 15507 | 61.56         |
| 0161960201      | 2003 Oct 27 | 13513 | 44.67         |
| 0164560501      | 2004 May 22 | 8007  | 26.97         |
| 0300520201      | 2005 Apr 28 | 10366 | 37.97         |
| 0300520301      | 2005 Sep 22 | 10934 | 36.33         |
| 0311590101      | 2005 Nov 12 | 10917 | 39.57         |
| 0401413001      | 2006 May 22 | 5952  | 21.62         |
| 0401414001      | 2006 Nov 5  | 5592  | 21.82         |
| 0502710201      | 2007 May 5  | 4451  | 16.77         |
| 0502710301      | 2007 Nov 17 | 6138  | 24.81         |
| 0554510101      | 2009 Mar 21 | 3682  | 15.45         |
| 0601170301      | 2009 Sep 22 | 3570  | 15.61         |
| 0650920101      | 2011 Apr 11 | 4443  | 19.81         |
| 0670700201      | 2011 May 02 | 3741  | 16.99         |
| total           |             | 140584 | 533.38        |

Figure 1. The co-added RGS1 (first order) spectrum of RX J0720.4−3125 with a total exposure of 516 ks. The thin, solid black line represents the fit model, while the lower red line shows the fit model plus a narrow absorption feature seen at 568.6+0.2−1.5 eV with EW = −1.89+0.55−0.59 eV (errors denote 90% confidence level), see also Hambaryan et al. (2009) for comparison. We also mark the locations of instrumental features exemplarily in this figure (not shown in the spectra of the other neutron stars).

2.2 RX J1308.6+2127 (RBS1223)

The XMM-Newton EPIC-pn spectra of the M7 member RX J1308.6+2127 exhibit two broad Gaussian absorption features (Haberl 2007) with line energies of 0.30 keV and 0.23 keV (or one line at 0.30 keV or 0.29 keV, see Haberl et al. 2003), again below the RGS spectrum. Thus, these two lines appear as one broader line with a line energy at 0.205 keV, i.e. we use the Xspec model phabs*(bbodyrad+gaussian) and fixed the line energy for fitting, but released it for the error calculation. The XMM-Newton RGS observations of RX J1308.6+2127 sum up to 190 ks, where 170 ks are left after passing the GTI filters, see Table 2.

The co-added spectrum fits with χ²/d.o.f. = 1.32. Although having less counts than the co-added spectrum of RX J0720.4−3125, it can be clearly stated that no significant narrow absorption feature at 0.57 keV is detected. However, the model overpredicts the count numbers in the energy range from 0.48 keV to 0.60 keV, that can be interpreted as a new absorption feature – broader than the absorption feature in RX J0720.4−3125, but too narrow to be detected in EPIC-pn.

Including a further (broader) Gaussian absorption line at 0.53 keV decreases χ²/d.o.f. to 1.13. The co-added RGS1 spectrum is shown in Figure 2. Schwope et al. (2007) reported one absorption feature at 0.20−0.39 keV and a further broad feature either at 0.46 keV or at 0.73 keV in the XMM-Newton EPIC-pn spectra of RX J1308.6+2127. The second feature does not correspond to the line at 0.53 keV found here and there is no evidence for the feature found

the data used by Hambaryan et al. (2009) together with the new XMM-Newton observations, that adds up to 650 ks in total (533 ks after GTI filtering), see Table 1.

The X-ray spectra of RX J0720.4−3125 are best modelled with a blackbody and a broad absorption feature at 300 eV (probably caused by proton cyclotron resonance) that is represented by a Gaussian absorption line (see Hohle et al. 2009, 2010; Haberl 2007; Haberl et al. 2006; de Vries et al. 2004), both absorbed due to the interstellar medium. We use the Xspec model phabs*(bbodyrad+gaussian). However, the RGS1 spectrum begins at energies of 0.35 keV, i.e. the centre of the cyclotron line is outside the spectrum (at 0.3 keV) and the information of the continuum yielding the blackbody normalisation, N_H and the properties of the cyclotron line is limited to lower energies. Thus, these parameters are degenerated (a higher N_H value can be compensated by a broader and deeper cyclotron line etc.). For such investigations the EPIC-pn spectra are much more suitable, but pn does not provide the spectral resolution that is required here.

Therefore, we fitted the co-added RGS1 spectrum keeping all parameters free for fitting but fixed the line energy of the cyclotron line at 0.3 keV (also for the error calculations).

We fitted the RGS1 spectrum with this model, using the photons from 0.35 − 1.0 keV. The co-added spectrum fits with χ²/d.o.f. = 1.50. For the narrow absorption feature we included a further Gaussian line at 0.57 keV. The fit including the narrow absorption feature yields χ²/d.o.f. = 1.42. Note, that no instrumental features are present around 0.57 keV, i.e. supporting an astrophysical origin. The fit results are listed in Table 8 and the spectrum is shown in Figure 1.

We confirm the presence of a narrow absorption feature at 568.6+0.2−1.5 eV with an equivalent width (EW) of EW = −1.89+0.55−0.59 eV (that corresponds to 5.6σ significance).
in Schwope et al. (2007) in our co-added RGS1 spectrum. The differences between RGS and pn were reduced in the last years (e.g. compared to Haberl et al. 2003 and Schwope et al. 2007) due to new calibrations. Thus an up-dated combined RGS and pn analysis is required with the new calibrations. Maybe the X-ray spectrum of RX J1308.6+2127 is much more complex and the absorption features change with time (since the work of Schwope et al. 2007, we have five more observations available). We stress that the RGS detector exhibits strong features in the energy range from 0.48 keV to 0.60 keV, but these features are narrow compared to the feature we found at 0.53 keV (that is not seen in the brighter spectrum of e.g. RX J0720.4–3125). Thus, the new absorption feature is not of an instrumental origin. Since the line centre of the new absorption feature lies at 0.53 keV (that is not seen in the brighter spectrum), we found at 0.53 keV (that is not seen in the brighter spectrum of e.g. RX J0720.4–3125). Thus, the new absorption feature is not of an instrumental origin. Since the line centre of the new absorption feature lies at 0.53 keV (that is not seen in the brighter spectrum of e.g. RX J0720.4–3125). Thus, the new absorption feature is not of an instrumental origin.

### Table 2. As in Table 1, but for RX J1308.6+2127 (RBS1223).

| Obs. ID    | date     | counts | eff. exposure |
|------------|----------|--------|---------------|
| 0099010101 | 2001 Dec 31 | 946   | 8.83          |
| 0157360101 | 2003 Jan 1  | 3055  | 28.71         |
| 0163560101 | 2003 Dec 30 | 3019  | 29.80         |
| 0305900201 | 2005 Jun 25 | 1633  | 16.73         |
| 0305900301 | 2005 Jun 27 | 1487  | 14.74         |
| 0305900401 | 2005 Jul 15 | 1230  | 12.43         |
| 0305900601 | 2006 Jan 10  | 1576  | 16.72         |
| 0402850301 | 2006 Jun 8  | 545   | 5.53          |
| 0402850401 | 2006 Jun 16 | 842   | 8.34          |
| 0402850501 | 2006 Jun 27 | 913   | 9.48          |
| 0402850901 | 2006 Jul 5   | 662   | 7.11          |
| 0402850701 | 2006 Dec 27  | 993   | 10.34         |
| total      |          | 16901 | 168.76        |

### Table 3. As in Table 1, but for RX J1605.3+3249.

| Obs. ID    | date     | counts | eff. exposure |
|------------|----------|--------|---------------|
| 0073140001 | 2002 Jan 9  | 2717  | 20.08         |
| 0073140201 | 2002 Jan 15 | 3715  | 27.23         |
| 0073140501 | 2002 Jan 19 | 3009  | 22.21         |
| 0157360401 | 2003 Jan 17 | 4470  | 30.98         |
| 0302140501 | 2006 Feb 12  | 748   | 5.91          |
| total      |          | 14660 | 107.01        |

#### 2.3 RX J1605.3+3249

The first report of a narrow absorption feature in the co-added RGS spectra of an isolated NS was published by van Kerkwijk et al. (2004), who found an absorption line at 0.57 keV in the spectra of RX J1605.3+3249. Since then, nine further XMM-Newton observations of RX J1605.3+3249 were performed, i.e. 14 in total. However, almost all observations after February 2006 are strongly contaminated by high background and did not pass the GTI filtering. Finally, our sample of observations is not much different from that used by van Kerkwijk et al. (2004), see Table 3. We only could add observation 0302140501 (6 ks left after GTI filtering), but omitted observation 0302140601 (used in van Kerkwijk et al. 2004). The total exposure time sums up to 110 ks.

van Kerkwijk et al. (2004) found a broad absorption feature at 0.493 keV, again associated with a possible cyclotron line, i.e. we use the model `phabs*(bbodyrad+gaussian)` here too. This line energy lies well within the RGS energy range, but the best fit leads to a line energy at 0.403 keV that has to be fixed for the error calculation. Therefore, the $N_H$ value and the blackbody temperature lies below the values listed in van Kerkwijk et al. (2004), but is consistent within the errors, see Table 8. The co-added spectrum fits with $\chi^2$/d.o.f. = 1.22.

Adding a further Gaussian absorption feature, the fit yields $\chi^2$/d.o.f. = 1.11. We confirm the presence of an absorption line at $576.1^{+2.5}_{-2.7}$ eV with $EW = -3.2^{+1.5}_{-1.8}$ eV, with the 3.5 $\sigma$ significance, as reported in van Kerkwijk et al. (2004). The co-added RGS spectrum of RX J1605.3+3249 is shown in Figure 3.

#### 2.4 RX J1856.4–3754

This NS is the brightest member of the M7 and is known to exhibit no features in XMM-Newton EPIC-pn and Chandra HRC-S/LETG spectra (Burwitz et al. 2001, 2003) and is constant over time. Thus, RX J1856.4–3754 is used as calibration source for X-ray telescopes. Therefore, the XMM-Newton observations sum up to 1000 ks, where 880 ks remain after the GTI filtering, see Table 4. Although Burwitz et al. (2001, 2003) found no absorption feature we include this source as well, since the co-added RGS spectra of RX J1856.4–3754 were not investigated before.

Likewise Burwitz et al. (2001, 2003), we apply the Xspec model `phabs*(bbodyrad)`, where the fit yields $\chi^2$/d.o.f. = 1.16 (see Table 8). The spectrum of RX J1856.4–3754 is...
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2.5 Geminga (PSR J0633+1746)

The first spectrum of Geminga with a sufficiently large count number was published by Halpern & Ruderman (1993), using ROSAT data. They found the Geminga spectrum is best modelled with two blackbodies having $kT_{\text{eff}} = 43$ eV and $kT_{\text{eff}} = 260$ eV, respectively. Using new ROSAT data, Halpern & Wang (1997) identified a power-law component above 2 keV with $\Gamma = 0.5 - 1.5$ (the most recent value is $\Gamma = 1.72 \pm 0.10$, see Jackson et al. 2002; Caraveo et al. 2004). Therefore, we use phabs*(bbbodyrad+pow) for the data fitting.

Although Geminga was frequently observed with XMM-Newton (240 ks after GTI filtering), the total number of counts is only 3,100, i.e. less than half the photons Halpern & Ruderman (1993) could use in their first Geminga spectrum (but with lower spectral resolution), see Table 5.

Since the co-added RGS spectrum of Geminga has the lowest count number in our sample and the hot blackbody dominates the spectrum above 1 keV, but is strongly superimposed by the power-law (see e.g. Figure 1 in De Luca et al. 2005), we find the best fit with a negligible normalisation of the hot blackbody, whereas the power-law is clearly visible. Thus, we applied the model phabs*(bbbodyrad+pow). The fit yields $\chi^2/d.o.f. = 1.21$ and the results are shown in Table 8. We find no evidence for an absorption feature like the hot blackbody. The results are shown in Table 8.

2.6 PSR B0656+14

The first investigation of the emission of PSR B0656+14 was performed with ROSAT data by Possenti et al. (1996), who modelled the spectrum with a blackbody and a second component that could be either a further blackbody or...
a power-law. Later, Greiveldinger et al. (1996) applied the three component model (two blackbodies and a power-law with $\Gamma = 1.5 \pm 1.1$) that yields the best fit. This model was later confirmed by Pavlov et al. (2002) using Chandra data. Marshall & Schulz (2002) found no evidence for spectral features in the Chandra spectra of PSR B0656+14, but used only two blackbodies (and no power-law) for their fit model. Today, only one RGS observation of PSR B0656+14 is available (Table 6). But this observation yields more counts than e.g. all Geminga observations in total.

We first fitted the RGS1 spectrum of PSR B0656+14 with \textit{phabs*(bbodyrad+bbodyrad+pow)}. Both blackbodies dominate the spectrum in the RGS energy range, but the power-law becomes significant above 2 keV (see Figure 2 in De Luca et al. 2005), where the RGS1 spectrum has much less counts. Thus, the power-law is negligible and we further on use the model \textit{phabs*(bbodyrad+bbodyrad)} (likewise in Marshall & Schulz 2002). The fit yields $\chi^2/d.o.f. = 0.88$ and the spectral properties are listed in Table 8.

We find no evidence for a narrow absorption feature in the RGS1 spectrum of PSR B0656+14 (Figure 6) and thereby confirm the results in Marshall & Schulz (2002). The count number of the RGS1 spectrum would have been sufficiently high to detect an absorption feature as found e.g. in the spectrum of RX J0720.4–3125, if present.

2.7 PSR B1055-52

The first spectral investigation of PSR B1055-52 was performed by Oegelman & Finley (1993) using ROSAT data. Like in the case of PSR B0656+14, the best fit model required a blackbody and a further component that could be a second blackbody or a power-law with $\Gamma \approx 4$. Combining ROSAT and Chandra data, Pavlov et al. (2002) showed that an adequate fit model requires three components: two blackbodies and a power-law with $\Gamma \approx 1.7$. Therefore we first use \textit{phabs*(bbodyrad+bbodyrad+pow)}.

 Altogether, the RGS1 data of PSR B1055-52 sum up to 95 ks (90 ks after GTI filtering) with $\approx 4\,000$ photons (Table 7). For the same reasons as discussed in the case of Geminga, we found the best fit for a negligible normalisation of the second, hotter, blackbody. Therefore, we applied the model \textit{phabs*(bbodyrad+pow)}, that fits with $\chi^2/d.o.f. = 1.16$ (Table 8).

In contrast to the other 3M, PSR B1055-52 seems to exhibit a weak absorption feature at 0.57 keV. Similar to those found in the co-added RGS1 spectra of RX J0720.4–3125 and RX J1605.3+3249. To check this, we add a Gaussian absorption line to our fit model (Figure 7). With the new model, the $\chi^2/d.o.f.$ value does not change significantly to 1.15, but the fit easily finds its minimum with the new line at $565_{-26}^{+9.6}$ eV with EW $= -5.7_{-9.2}^{+11.6}$ eV. This feature is not consistent with the continuum within 2$\sigma$, i.e. less significant than the narrow absorption feature in RX J1605.3+3249, but we stress that the total count number in the case of the co-added RGS1 spectrum of PSR B1055-52 is more than three times less than in the case of RX J1605.3+3249, i.e. further observations are required to verify this absorption feature.

2.8 XMM-Newton Results

We co-added all available RGS data of the four brightest M7 (RX J0720.4–3125, RX J1308.6+2127/RBS1223,
Table 8: Fit results from the co-added XMM-Newton RGS spectra of four M7 and the 3M. The sizes of the emitting areas (\(\text{norm}\)) are calculated from the normalisations of the X-ray blackbodies and correspond to a distance of 300 pc, except in the case of RX J1856.4–3754 (130 pc, Walter et al. 2010) and PSR B1055-52 (750 pc, Kramer et al. 2003). The line energies of the broad absorption features are always fitted as free parameters (except in the case of RX J0720.4–3125, where the line energy was always fixed), but fixed for the error calculation. The equivalent widths (EW) of these broad absorption features have no errors since the lines reach partly out of the energy range of the RGS spectrum. All errors denote 90% confidence level.

| model component | unit | RX J0720.4–3125 | RX J1308.6+2127 | RX J1605.3+3249 | RX J1856.4–3754 | Geminga | PSR B0656+14 | PSR B1055-52 |
|-----------------|------|-----------------|-----------------|-----------------|-----------------|--------|--------------|--------------|
| \(N_{\text{H}}\) | \(10^{20}/\text{cm}^2\) | 1.66_{-0.65}^{+0.52} | 1.6_{-1.5}^{+1.6} | 0.72_{-0.72}^{+1.72} | \(\leq 0.32\) | 3.9_{-1.9}^{+1.1} | 0.12_{-0.12}^{+1.64} | 2.4_{-2.4}^{+3.4} |
| \(\text{bbodyrad}_1\) | \(\text{eV}\) | 85.0_{-1.6}^{+1.7} | 78.3_{-4.3}^{+4.6} | 85.3_{-4.2}^{+3.1} | 62.67_{-0.60}^{+0.25} | 33.2_{-12.1}^{+9.2} | 67.9_{-6.7}^{+3.6} | 72.0_{-7.8}^{+9.5} |
| \(\text{norm}_1\) | \(\text{km}\) | 6.4_{-0.61}^{+0.64} | 6.7_{-1.4}^{+1.8} | 4.81_{-0.72}^{+1.44} | 5.015_{-0.035}^{+0.260} | \(\leq 68\) | 9.5_{-0.72}^{+0.66} | 8.8_{-4.0}^{+4.3} |
| \(\text{bbodyrad}_2\) | - | - | - | - | - | - | 170_{-0.88}^{+0.44} | - |
| \(\text{norm}_2\) | \(\text{km}\) | - | - | - | - | - | 0.373_{-0.088}^{+0.808} | - |
| \(\text{Gaussian}_1\) | \(\text{eV}\) | 300 (fixed) | 205.83 (fixed) | 403 (fixed) | - | - | - | - |
| \(\sigma_1\) width | \(\text{eV}\) | 100.7_{-12.4}^{+8.5} | 135.7_{-3.2}^{+2.5} | 100.1_{-5.7}^{+7.0} | - | - | - | - |
| \(\text{EW}_1\) | \(\text{eV}\) | -55.2 | -163 | -65.2 | - | - | - | - |
| \(\text{power law}\) | - | - | - | - | - | - | 2.67_{-0.91}^{+1.27} | - |
| \(\Gamma\) | - | - | - | - | - | - | 3.8_{-2.4}^{+1.8} | - |
| \(\text{norm}\) | \(\text{ph}/\text{keV}/\text{cm}^2/\text{s}\) at 1 keV | - | - | - | - | 9.1_{-2.3}^{+2.5} \times 10^{-5} | - | 7.6_{-4.3}^{+4.0} \times 10^{-5} |
| \(\chi^2_{\text{red}}/\text{d.o.f.}\) | - | 1.50/456 | 1.32/208 | 1.22/110 | 1.16/759 | 1.21/66 | 0.88/305 | 1.16/121 |
| \(\text{Gaussian}_2\) | \(\text{eV}\) | 568.6_{-1.9}^{+1.8} | 535.3_{-3.4}^{+7.4} | 576.1_{-2.7}^{+2.5} | - | - | - | 565.0_{-2.9}^{+26.0} |
| \(\sigma_2\) width | \(\text{eV}\) | 4.8_{-1.9}^{+1.4} | 35_{-14}^{+24} | 3.3_{-3.3}^{+4.3} | - | - | - | 5.6_{-5.9}^{+26.1} |
| \(\text{EW}_2\) | \(\text{eV}\) | -1.89_{-0.62}^{+0.56} | -20_{-1.8}^{+10} | -3.2_{-1.8}^{+1.5} | - | - | - | -5.7_{-9.2}^{+4.6} |
| \(\text{significance}\) | \(\sigma\) | 5.6 | 3.2 | 3.5 | - | - | - | 2.1 |
| \(\chi^2_{\text{red}}/\text{d.o.f.}\) | - | 1.42/453 | 1.13/205 | 1.11/107 | - | - | - | 1.15/118 |
RX J1605.3+3249 and RX J1856.4–3754) and the 3M; Geminga, PSR B0656+14 and PSR B1055-52. We confirm the narrow absorption features at 0.57 keV in the spectra of RX J0720.4–3125 and RX J1605.3+3249 as reported in earlier work by Hambaryan et al. (2009) and van Kerkwijk et al. (2004), respectively. We found a new absorption feature at 0.53 keV in the co-added RGS spectrum of RX J1308.6+2127, that is broader than those found in the case of RX J0720.4–3125 and RX J1605.3+3249.

The co-added spectra of RX J1856.4–3754 and PSR B0656+14 are featureless, while the count number in the co-added spectra of Geminga is not sufficiently high to exclude such weak features. There might be a new absorption feature (comparable to those in the spectra of RX J0720.4–3125 and RX J1605.3+3249) present in the co-added spectrum of PSR B1055-52.

We fitted the absorption features using an additive Gaussian line and checked our results with the multiplicative gabs model. For both models we obtain exactly the same values for the equivalent widths. Our results are summarised in Table 8 and we will discuss them in the next sections.

3 THE CHANDRA HRC-S/LETG SPECTRA OF RX J0720.4–3125 AND RX J1856.4–3754

Hambaryan et al. (2009) considered the absorption feature at 0.57 keV could be caused by gravitational redshifted OVIII. If true, OVII should appear at 0.48 keV with the same redshift (\(g = 1.17\), see the more detailed discussion in section 4). However, we found no evidence for such a feature in the co-added RGS spectrum, see Figure 1. Therefore we also analysed the Chandra HRC-S/LETG spectra of RX J0720.4–3125 and RX J1856.4–3754 for comparison, since RX J1856.4–3754 does not exhibit any features in the Chandra HRC-S/LETG spectra (Burwitz et al. 2001, 2003). The Chandra HRC-S/LETG (Juda 1996; Evans 1997; Juda 1997; Kraft et al. 1997) data were analysed with CIAO 4.1. We created own GTI files using dmgti and filtered those events for data reduction with less than 60 s/1000 counts per channel (source plus background and background) from both first orders were cut out within the standard extraction windows. The HRC-S/LETG spectra were added using the CIAO command add grating orders to add the first orders (all other orders have a negligible count number) and add grating spectra to add the HRC-S/LETG spectra. To prepare the HRC-S/LETG data for spectroscopic fitting in Xspec, the background was generated with the command fg–bkg. Altogether, the co-added HRC-S/LETG spectra have 429 ks exposure time (see Table 9). For details of the reduction of the Chandra data we also refer to Hohle et al. (2010).

We fitted the co-added Chandra HRC-S/LETG spectrum of RX J0720.4–3125 with the same model as in Table 8 (without the narrow absorption feature at 0.57 keV), using the photons from 0.15 – 1.0 keV, but ignoring the edges of the feature in the co-added RGS spectrum, see Figure 1. Therefore we also analysed the Chandra HRC-S/LETG spectra of RX J0720.4–3125 and RX J1856.4–3754 for comparison, since RX J1856.4–3754 does not exhibit any features in the Chandra HRC-S/LETG spectra (Burwitz et al. 2001, 2003). The Chandra HRC-S/LETG (Juda 1996; Evans 1997; Juda 1997; Kraft et al. 1997) data were analysed with CIAO 4.1. We created own GTI files using dmgti and filtered those events for data reduction with less than 60 s/1000 counts per channel (source plus background and background) from both first orders were cut out within the standard LETG spectral extraction windows. The HRC-S/LETG spectra were added using the CIAO command add grating orders to add the first orders (all other orders have a negligible count number) and add grating spectra to add the HRC-S/LETG spectra. To prepare the HRC-S/LETG data for spectroscopic fitting in Xspec, the background was generated with the command fg–bkg. Altogether, the co-added HRC-S/LETG spectra have 429 ks exposure time (see Table 9). For details of the reduction of the Chandra data we also refer to Hohle et al. (2010).

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We fitted the co-added Chandra HRC-S/LETG spectrum of RX J0720.4–3125 with the same model as in Table 8 (without the narrow absorption feature at 0.57 keV), using the photons from 0.15 – 1.0 keV, but ignoring the edges of the

| Obs. Id. | Start Date | Counts | Eff. exposure |
|---------|------------|--------|---------------|
| 368     | 2000 Feb 1 | 580    | 2.10          |
| 745     | 2000 Feb 2 | 3      | 0.14          |
| 369     | 2000 Feb 4 | 2660   | 6.12          |
| 5305    | 2004 Feb 27| 9691   | 35.68         |
| 5581    | 2005 Jan 23| 17703  | 62.05         |
| 5582    | 2005 Jun 1 | 19639  | 69.69         |
| 6364    | 2005 Aug 27| 9323   | 31.68         |
| 6569    | 2005 Oct 8 | 4448   | 16.14         |
| 7177    | 2005 Oct 9 | 2067   | 7.18          |
| 7243    | 2005 Dec 14| 4992   | 17.05         |
| 7244    | 2005 Dec 15| 4295   | 16.16         |
| 7245    | 2005 Dec 16| 2964   | 11.10         |
| 5584    | 2005 Dec 17| 2972   | 10.87         |
| 7251    | 2006 Sep 9 | 2713   | 10.59         |
| 10861   | 2009 Jan 20| 2948   | 11.11         |
| 10700   | 2009 Feb 14| 5478   | 21.61         |
| 10701   | 2009 Sep 11| 8228   | 32.36         |
| 11820   | 2010 Jun 19| 8650   | 33.56         |
| 13181   | 2010 Nov 18| 4937   | 19.90         |
| 13188   | 2010 Nov 19| 3709   | 14.04         |
| total   |            | 118000 | 429.60        |
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Table 10. Fit results from the co-added Chandra HRC-S/LETG spectrum of RX J0720.4−3125 (blackbody with Gaussian absorption lines, where EW denotes the equivalent widths) and RX J1856.4−3754 (blackbody). The sizes of the emitting areas (norm) are calculated from the normalisations of the X-ray blackbodies and correspond to a distance of 300 pc for RX J0720.4−3125 (Kaplan et al. 2007; Eisenbeiss 2011) and 130 pc for RX J1856.4−3754 (Walter et al. 2010). All errors denote 90% confidence level.

| model component | unit     | RX J0720.4−3125 | RX J1856.4−3754 |
|-----------------|----------|----------------|-----------------|
| N_H             | 10^{20}/cm^2 | 0.886^{+0.048}_{-0.047} | 0.800^{+0.033}_{-0.052} |
| bbodyrad kT     | eV       | 92.4^{+1.0}_{-1.0} | 63.28 ± 0.48 |
| norm            | km       | 4.5^{+1.1}_{-1.1} | 4.95 ± 0.12 |
| Gaussian_1      |          |                |                 |
| lineE_1         | eV       | 293.4^{+5.0}_{-5.0} | 3125.48 keV     |
| σ_1 width       | eV       | 50.45^{+9.0}_{-9.0} |                |
| EW_1            | eV       | −29.6^{+4.7}_{-4.6} |                |
| χ^2_{red}/d.o.f.|          | 1.07/258        | 1.02/505        |
| Gaussian_2      |          |                |                 |
| lineE_2         | eV       | 482.6^{+5.1}_{-4.0} |                |
| σ_2 width       | eV       | 7.8^{+0.9}_{-0.9} |                |
| EW_2            | eV       | −1.83^{+0.98}_{-2.76} |                |
| significance σ  |          | 3.0             |                |
| Gaussian_3      |          |                |                 |
| lineE_3         | eV       | 529.4^{+2.2}_{-2.7} |                |
| σ_3 width       | eV       | 3.8^{+2.9}_{-1.6} |                |
| EW_3            | eV       | −1.79^{+0.74}_{-0.64} |                |
| significance σ  |          | 3.9             |                |
| Gaussian_4      |          |                |                 |
| lineE_4         | eV       | 566.4^{+6.6}_{-7.2} |                |
| σ_4 width       | eV       | 7.4^{+5.8}_{-4.0} |                |
| EW_4            | eV       | −2.0^{+1.2}_{-1.3} |                |
| significance σ  |          | 2.7             |                |
| χ^2_{red}/d.o.f.|          | 1.02/249        |                 |

chip gaps at 0.2390 – 0.2432 keV, 0.248 – 0.252 keV and 0.2180 – 0.2215 keV, to avoid systematic fit errors. The fit yields χ^2/d.o.f. = 1.07 for 258 degrees of freedom applying the standard model with blackbody radiation and the broad absorption feature at 0.3 keV. The spectral properties are listed in Table 10 and are consistent to those derived from XMM-Newton EPIC-pn spectra, see Hohle et al. (2009) and Table 8. Note, the averaged temperature of RX J0720.4−3125 derived from the Chandra HRC-S/LETG spectrum (Table 10) is different to that obtained with the RGS data (Table 8), since the source is variable and the observations of the different instruments were performed at different times. In addition, possible systematic errors in the effective area calibrations between both instruments can lead to different temperatures.

The narrow absorption feature at 0.57 keV found by Hambaryan et al. (2009) should also be present in the co-added Chandra HRC-S/LETG spectrum of RX J0720.4−3125. Indeed, regarding the fit residuals in Figure 8, such an absorption feature appears at the particular energy range, but less clear than in Figure 1. Two other absorption features at 0.48 keV and 0.53 keV seem even more significant with respect to the continuum (Figure 8), thus, in addition to the narrow absorption feature found by Hambaryan et al. (2009), two other Gaussian absorption lines (at 0.48 keV and 0.53 keV) are added to the fit model.

Fitting the data with the additional lines, the fit yields χ^2/d.o.f. = 1.02 with 249 degrees of freedom. Since all lines are rather weak, for a cross-check Chandra pipeline products were used as well as reprocessed data for the co-added spectrum together with two different absorption models (phabs and tbabs) for the ISM and different grouping of the co-added spectra using the task grppha. In all cases, the lines are present, see Figure 8. The parameters of the absorption lines are listed in Table 10.

The absorption feature at 0.48 keV is not seen in the co-added RGS spectrum of RX J0720.4−3125, thus we also co-added all available Chandra HRC-S/LETG spectra of the much brighter NS RX J1856.4−3754 (for the individual observations we refer to Burwitz et al. 2001, 2003; Drake et al. 2002) for comparison.

For the fitting procedure we applied the same model as in subsection 2.4. The fit results are listed in Table 10 and

\footnote{The EPIC-pn spectra are fitted for the individual observations in one session. Since RX J0720.4−3125 is variable, only N_H, line energy and line σ are kept constant in time.}
and 0.57 keV, see also Table 10. The fit residuals of RX J1856.4−3125 are absent in the residuals of RX J0720.4−3125. The red dashed lines mark the line centres of the three absorption features.

are in good agreement to the values published in Burwitz et al. (2001, 2003). The fit residuals of the Chandra HRC-S/LETG spectrum of RX J1856.4−3125 do not exhibit the absorption features we found in the fit residuals of the Chandra HRC-S/LETG spectrum of RX J0720.4−3125, see Figure 9. Thus, although weak, the features found in the spectrum of RX J0720.4−3125 are not of an instrumental origin.

4 DISCUSSION

The identification of narrow absorption lines in the X-ray spectra of highly magnetised NSs is non-trivial: If a line originates from the NS atmosphere, it is redshifted by a factor of \( g_r = 1.11 \) (\( M = 1 \, M_\odot, \, R = 16 \, \text{km} \)) to \( g_r = 2.00 \) \( (M = 2 \, M_\odot, \, R = 8 \, \text{km}) \) and the ion itself is not known. Considering abundances, lines in NS spectra may originate from highly ionised mid-Z elements or iron (Mori & Ho 2007), probably from the \( K_\alpha \) lines, since they would cause the most strongest features. The strong magnetic field would shift and broaden the spectral lines.

An alternative interpretation is the interstellar origin of these absorption features, caused by the ISM, in particular in the LB, see e.g. Lallement et al. (2003) or Breitschwerdt & de Avillez (2006); Breitschwerdt et al. (2009). Some of the NSs in this work are likely located within the LB (e.g. RX J1856.4−3754), whereas other sources are outside (e.g. PSR B1055-52). We will discuss the two interpretations in the following sections.

4.1 Absorption features from the neutron star atmosphere

The detected line at 0.57 keV corresponds to OVII or OVI (Hirata & Horaguchi 1995) without gravitational redshift, as discussed in Hambaryan et al. (2009). This line is actually a blend that mainly consists of the \( K_\alpha \) resonance line \((1s^2 - 1s2p^1P_1(\pi))\) at 573.95 eV of the triplet of He-like oxygen (OVII). This resonance line is superimposed with numerous weak OVI lines (see Hirata & Horaguchi 1995; Kaastra et al. 2009 for details), therefore the absorption feature at 0.57 keV appears not as a perfect Gaussian and the equivalent widths and the line widths (\( \sigma \)) are larger than expected from the single, fully resolved lines (note, the resolution of RGS1 at 0.57 keV is \( \approx 1.7 \, \text{eV} \)). The intercombination line \((1s^2 - 1s2p^3P_{1,2}(i))\) at 568.63 eV and the forbidden line \((1s^2 - 1s2s^3S_1(f))\) at 560.99 eV of the OVII triplet do not contribute to the absorption feature, since they appear only in emission (not detected in our spectra).

If highly ionised oxygen is present close to the NS surface, the OVIII Ly\( \alpha \) line \((1s - 2p; \ i.e. \ OVIII \ K_\alpha)\) at 653.62 eV could appear at \( \approx 0.57 \, \text{keV} \) with a reasonable redshift of \( g_r = 1.16 \) (or \( g_r = 1.17 \)) and the corresponding OVII \( K_\alpha \) resonance line should appear at 0.48 keV \( (g_r = 1.17) \). In Hambaryan et al. (2009) it is argued, that such an absorption feature may be detected in the co-added RGS spectra of RX J0720.4−3125.

We find no evidences for such a feature, neither in the co-added RGS spectra of RX J0720.4−3125, nor in the co-added RGS spectra of RX J1605.3+3249 (see Figure 1 or Figure 3). The RGS detector exhibits an intrinsic feature at 0.48 keV that may superimpose a weak feature and inhibit a possible detection. However, we find such an absorption feature in the co-added Chandra HRC-S/LETG spectra of RX J0720.4−3125 (Figure 8 and Figure 9). This feature is rather weak, but comparable (regarding to its broadness) to the absorption feature at 0.57 keV (Figure 1), thus should be seen in the co-added RGS spectra of RX J0720.4−3125 too (although superimposed by a much narrower instrumental feature).

Intriguingly, the absorption feature at 0.48 keV (if real, see Figure 9) would fit the interpretation of a gravitational...
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redshifted line (implying a redshift of \( g_r = 1.17 \)) and such features are expected at the particular energy range from NS atmosphere models (see Mori & Ho 2007, in particular Figure 14 therein for 10^{13} \text{ G} field strength and 1 \text{ MK} surface temperature, as measured for RX J0720.4−3125). On the other hand, the absorption feature at 0.48 keV is not very significant and requires further confirmation. The measured magnetic field strengths of the M7 (and the 3M) significantly increase the binding energy of atoms, if close to the NS. Under these conditions, the temperatures of \( \approx 1 \text{ MK} \) might be too low to generate significant amounts of highly ionised oxygen, as discussed in Hambaryan et al. (2009). However, the atomic physics is not well understood for magnetic fields of about \( B \approx 10^{13} \text{ G} \).

Note, there is no such feature (at 0.48 keV) expected from the ISM (CVI would appear in this energy range, but significantly weaker, Hirata & Horaguchi 1995; Kaastra et al. 2009). An absorption feature at 0.65 keV (OVIII at rest, see Hambaryan et al. 2009) remains undetected, probably due to the lack of photons in this energy range (if from the ISM, the high temperatures that are required to generate OVIII are not likely).

The absorption feature found at 0.53 keV in the Chandra HRC-S/LETG data of RX J0720.4−3125 (see Figure 8) likely originates from the K-edge of neutral oxygen OI (Kaastra et al. 2009) at rest. This indicates an overabundance of neutral oxygen in the line of sight or might result from inexact modeling of this structure. Although we use different ISM absorption models (e.g. phabs or tbabs), this particular feature remains.

The absorption feature at 0.57 keV is well detected in the XMM-Newton RGS spectrum of RX J0720.4−3125 (Hambaryan et al. 2009) and it appears (although weak) in the Chandra HRC-S/LETG spectra, i.e. its presence is certain. However, a similar feature is also detected in the co-added RGS spectra of RX J1605.3+3249 (van Kerkwijk et al. 2004 and Figure 3). The energies of the line centres are well fitted in both cases (Table 8), where the line centre of the absorption feature in the spectrum of RX J1605.3+3249 is shifted by \( \approx 7.0 \pm 4.5 \text{ eV} \) with respect to the line centre of the absorption feature in the spectrum of RX J0720.4−3125.

This shift cannot be explained by the same transition of a particular ion (e.g. OVII) at rest caused by different radial motion, since the required speed would be \( \approx 3500 \text{ km/s} \). Either the two lines represent different transitions \( (1s^2−1s2p^3P_1(r)) \) at 573.95 eV in the case of RX J1605.3+3249 and \( 1s^2−1s2p^3P_{1,2}(i) \) at 568.63 eV in the case of RX J0720.4−3125 (both for OVII at rest) – but that raises the question why one transition is completely suppressed and why the intercombination line at 568.6−\text{1.5} eV (RX J0720.4−3125) is seen in absorption, not in emission. Alternatively, the shift might be caused by a slightly different gravitational redshift due to different NS compactness (\( g_r = 1.14 \) for RX J1605.3+3249) and both absorption features are caused by the OVIII Ly_α/Kα line.

We found a similar feature at 0.57 keV in the co-added RGS spectrum of PSR B1055−52. However, the spectrum has not enough counts to identify this line undoubtedly and to determine the line energy of the line centre sufficiently accurate.

Note, spectral lines originating from the NS surface should appear splitted (and shifted) due to the Zeeman-effect (Sarazin & Bahcall 1977) and broadened by pressure (Paerels 1997), that is not considered in this interpretation. Furthermore, the magnetic field is not constant over the NS surface, i.e. the lines should be broadened due to the contributions from different surface patches.

4.2 Absorption features of an interstellar or circumstellar origin

The distances of RX J0720.4−3125 and RX J1605.3+3249 are \( \approx 195−530 \text{ pc} \) (from direct parallax measurements, Kaplan et al. 2007; Eisenbeiss 2011) and \( \approx 325−390 \text{ pc} \) (estimated from extinction models, Posselt et al. 2007), respectively. Given the average volume density of OVII \( \rho_{\text{OVII}} = (1.35−2.84) \times 10^{-6} \text{ cm}^{-3} \) in the ISM (Yao & Wang 2005, assuming that oxygen is completely ionised to OVII), the expected OVII column densities for these two NSs are \( N_{\text{OVII}} = 1.2 \times 10^{14}−4.1 \times 10^{15} \text{ cm}^{-2} \) and a factor of two or three larger for PSR B1055−52, since this NS is more distant (Kramer et al. 2003). The hydrogen column densities from these three NSs are in the order of \( N_{\text{H}} = 10^{20} \text{ cm}^{-2} \) (Table 8). Applying the oxygen abundance relative to hydrogen \( n_{\text{O}}/n_{\text{H}} = 4 \times 10^{-4} \), Anders & Grevesse 1989), the expected column density of OVII should be in the order of \( N_{\text{OVII}} = 10^{16} \text{ cm}^{-2} \) (again assuming that oxygen is completely ionised to OVII).

The measured equivalent widths of the narrow absorption features at 0.57 keV yield \( N_{\text{OVII}} = 3 \times 10^{15}−10^{16} \text{ cm}^{-2} \) (RX J0720.4−3125), \( N_{\text{OVII}} = 3 \times 10^{16}−10^{20} \text{ cm}^{-2} \) (RX J1605.3+3249) and \( N_{\text{OVII}} \geq 10^{15} \text{ cm}^{-2} \) (PSR B1055−52), taking fit errors (Table 8) and different velocity dispersions (Futamoto et al. 2004) into account and assuming that the absorption feature at 0.57 keV is a pure line (not a blend).

Hambaryan et al. (2009) discussed a possible circumstellar origin of the absorption feature at 0.57 keV in the RGS spectra of RX J0720.4−3125 to explain this difference of the column densities and showed that the absorption feature might be (partly) caused by an ambient medium surrounding RX J0720.4−3125 in \( \approx 10^5 \text{ km distance from the NS, superimposed by absorption lines from the ISM.} \) The model in Hambaryan et al. (2009) is also applicable to RX J1605.3+3249 and PSR B1055−52, since both NSs have temperatures and magnetic field strengths comparable to that of RX J0720.4−3125. However, circumstellar disks surrounding isolated NSs with ages of the order of million years should be rare. Thus, it is unlikely that three sources out of seven in our sample host a disk.

Regarding the equivalent widths and the significance of the detection, the strongest narrow absorption features are present in the spectra of RX J0720.4−3125 and RX J1605.3+3249. Both NSs are located outside the LB (Lallement et al. 2003), i.e. are embedded in a denser

\[ 7 \text{ With this value, RX J0720.4−3125 would exceed its Schwarzschild radius by a factor of 3.7, i.e. would have an intrinsic radius of 15.6 km (assuming a mass of 1.4 M}_\odot \text{ or 18.3 km at infinity. However, the absorption features may originate from regions above the NS surface. Then, the given values for the radius are upper limits.} \]
medium than in the solar vicinity. The LB hosts hot plasma containing highly ionised oxygen (Breitschwerdt & de Avillez 2006; Breitschwerdt et al. 2009), such as OVII or OVI that is in the line of sight to these NSs. In contrast, the closest NS, RX J1856.4−3754, is almost certainly located within the LB (the most recent parallax measurement yields a distance of ≈125 pc, see Walter et al. 2010) towards the Galactic centre, i.e. embedded in a thin medium and therefore should not exhibit the narrow absorption feature. The distance of RX J1308.6+2127 (RBS1223) is highly uncertain and ranges from ≈76 − 700 pc (see Haberl 2007 and references therein), but this NS has a high Galactic latitude and is located either within the LB (for smaller distances), or above the Galactic plane. Even in the latter case, RX J1308.6+2127 is still surrounded by a low density medium (the local chimney, see Lallement et al. 2003 who shows the distribution of measured column densities). Therefore, also the spectra of RX J1308.6+2127 should not exhibit narrow absorption features. Geminga and PSR B0656+14 are located at roughly the same region above the Galactic plane, probably within the local chimney (the distances range from 150 pc to 300 pc for both objects, see Caraveo et al. 1996; Brisken et al. 2003; Walter 2005), like in the case of RX J1308.6+2127. Both NSs do not exhibit narrow absorption features, although in the case of Geminga the count number of the co-added RGS spectrum is too low to allow a final statement.

Finally, the spectrum of PSR B1055-52 shows an uncertain absorption feature and this NS is likely located outside the LB and is probably the most distant object in our sample (Kramer et al. 2003 estimated 750 pc from dispersion measurements).

If caused by the ISM, other X-ray sources (particularly much more distant) like e.g. Cyg X–2 (Yao et al. 2009), LMXB GS 1826–238 (Pinto et al. 2010, and other Galactic low-mass X-ray binaries; Yao & Wang 2005) or Mrk 421 (Rasmussen et al. 2007; Kaastra et al. 2006, with 955 ks exposure time) should exhibit similar absorption features. While the expected OVII resonance line at 573.95 eV of an interstellar origin is clearly visible (in particular in Kaastra et al. 2006, Figure 2 therein and Rasmussen et al. 2007, Figure 1 therein), these sources do not show an absorption feature at 568.6 eV in their RGS spectra as detected in the case of RX J0720.4−3125. The line energy in the Chandra HRC-S/LETG spectra of RX J0720.4−3125 yields 566.4±0.6 eV (Table 10), i.e. this value is almost compatible (within its errors) with the energy of the OVII K$_\alpha$ resonance line at rest.

5 CONCLUSIONS

We investigated the co-added RGS spectra of the four brightest M7 (RX J0720.4−3125, RX J1308.6+2127/RBS1223, RX J1605.3+3249 and RX J1856.4−3754) and the 3M; Geminga, PSR B0656+14 and PSR B1055-52 and searched for narrow absorption features, in particular at 0.57 keV.

We find that those NSs, that are either nearby or located in a medium with low densities do not exhibit narrow absorption features, whereas those NSs, that are distant and surrounded by a dense medium do exhibit narrow absorption features. The equivalent widths of the narrow absorption features at 0.57 keV do not correlate with the N_H value, and hardly correlate with the distances (Figure 10).

Other well investigated X-ray sources (Cyg X–2 Yao et al. 2009, LMXB GS 1826–238 Pinto et al. 2010, Mrk 421 Rasmussen et al. 2007; Kaastra et al. 2006) do not exhibit an absorption feature at 568.6 eV as detected in the case of
Absorption features in the X-ray spectra of isolated Neutron Stars

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