Journal of Physics: Conference Series **496** (2014) 012015 doi:10.1088/1742-6596/496/1/012015

Observational constraints of the compactness of isolated neutron stars

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Abstract. We report on our observational attempt to constrain the compactness of the isolated neutron stars via X-ray spin phase-resolved spectroscopy. There are seven thermally emitting neutron stars known from X-ray and optical observations, which are young (up to few Myrs), nearby (hundreds of pc), and radio-quiet with blackbody-like X-ray spectra. A model with a condensed iron surface and partially ionized hydrogen-thin atmosphere allows us to fit simultaneously the observed general spectral shape and the broad absorption feature (observed at 0.3 keV) in different spin phases. We constrain a number of physical properties of the X-ray emitting areas, including their temperatures, magnetic field strengths at the poles, and their distribution parameters. In addition, we place some constraints on the geometry of the emerging X-ray emission and the gravitational redshift of three isolated neutron stars.

1. Introduction: Thermally Emitting Isolated Neutron Stars (INSs)

The studies of INSs can provide an important input in our understanding of neutron stars and can put stringent constraints on the possible form of the equation of state of superdense matter. Observations and modeling of the thermal emission by INSs allow us to infer their surface temperatures and their total fluxes measured by a distant observer, as well as to estimate their real parameters, such as their apparent radii, provided the distances to the INSs are known accurately. On the other hand, the detection and identification of any absorption or emission feature in the spectrum or a rotational phase-resolved spectroscopy of INSs allow us to determine gravitational redshift, which in turn permits us to determine directly their mass-to-radius M/R ratio (see, e.g. [5, 6]).

The *ROSAT* X-ray observatory has discovered a small group (so far 7) nearby, thermally emitting and radio-quiet INSs which have the following common characteristics: (a) soft spectra, well described by blackbody radiation with the temperature in the range 60-120 eV, (b) absence of other spectral features, (c) no association with a known supernova remnant (SNR), (d) absence of radio emission or X-ray pulsations and, finally, (e) large ratio of the X-ray to optical emission f_x/f_{opt}. It has been suggested that these objects are either old INSs whose surface is reheated by accretion from the interstellar medium or young cooling stars which radiate away their thermal energy acquired at birth. Meanwhile, intensive X-ray observations using *XMM-Newton* and *Chandra* telescopes, as well as observations of these objects in optical and ultraviolet (UV), demand a revision of this origin of the thermal emission and provide further intriguing physical insight. Indeed, X-ray pulsations were found in six objects (with periods clustered in the range from 3 to 11 sec) and the period derivatives were determined for some of them. In the classical $P - \dot{P}$ diagram for the radio-pulsars these INSs occupy the region which is intermediate between radio pulsars and magnetars. Their inferred characteristic magnetic field strengths are above 10^{13} G.

Furthermore, imaging CCD-spectroscopy with XMM-Newton uncovered absorption features in at least three of INSs. It is likely that another three INSs feature similar absorption lines. At the current resolution ($E/dE \sim 60$) these lines are well described by Gaussian absorption lines. Their interpretation is not unique and they have been attributed to magnetically shifted atomic transitions, cyclotron resonances or an absorption feature from condensed surface (atmosphere). The inferred magnetic field strengths are again above 10^{13} G.

Another surprise came with the optical and ultraviolet observations of the fluxes from INSs, which were found to lie generally a factor of $\sim 5-10$ above the extrapolation of the X-ray spectrum (the so-called "optical excess", see, e.g. [9]).

Here we present the results of a rotational phase-resolved X-ray spectroscopy of the three brightest INSs (RBS 1223, RX J0720.4−3125 and RX J1856.5−3754) based on the multi–epoch observations conducted by *XMM-Newton*.

2. Data analysis and results

High quality rotation phase resolved spectra are needed in order to fit using magnetized atmosphere models of neutron stars and to constrain their gravitational redshift [13, 6].

2.1. RBS 1223

RBS 1223 shows the highest pulsed fraction (13-42%, depending on energy band, see Fig. 1) and the strongest broad absorption feature [12] among thermally emitting INSs.

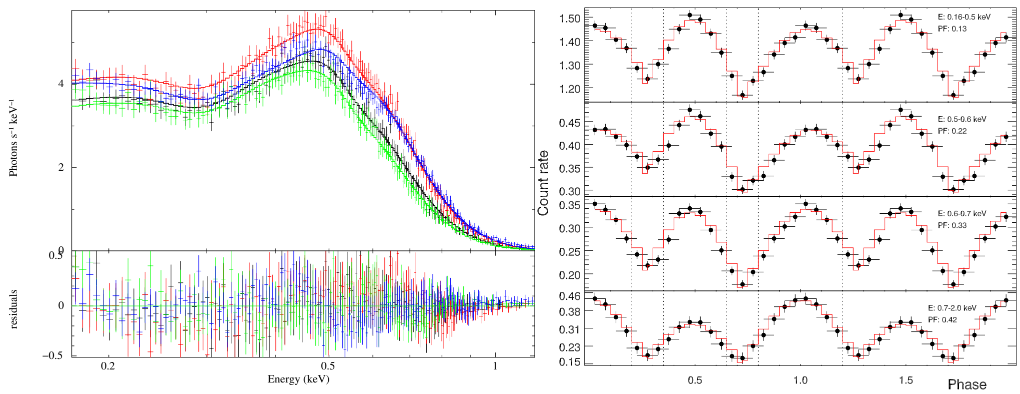

Figure 1. *XMM-Newton EPIC* pn co-added phase-averaged X-ray spectra (left panel) including primary and secondary peaks, first and second minima, and spin phase-folded light curves (right panel) in different energy bands of RBS 1223 combined from 12 pointed observations.

We used the data collected with *XMM-Newton* EPIC pn from the 12 publicly available (similar instrumental setup, i.e. Full Frame, Thin1 Filter) observations, in total comprising about 175 ks of effective exposure time. We extracted spin-phase resolved spectra with high S/N ratio (see Figs. 1 and 2) and fitted simultaneously with highly magnetized INS surface/atmosphere models [13]. These models are based on various local models and compute rotational phase dependent integral emergent spectra of INS using analytical approximations.

The basic model includes temperature/magnetic field distributions over isolated neutron star surface[1], viewing geometry and gravitational redshift. Three local radiating surface models are also considered, namely, a naked condensed iron surface [1] and partially ionized hydrogen model atmospheres, semi-infinite or finite atop of the iron condensed surface. The observed phase

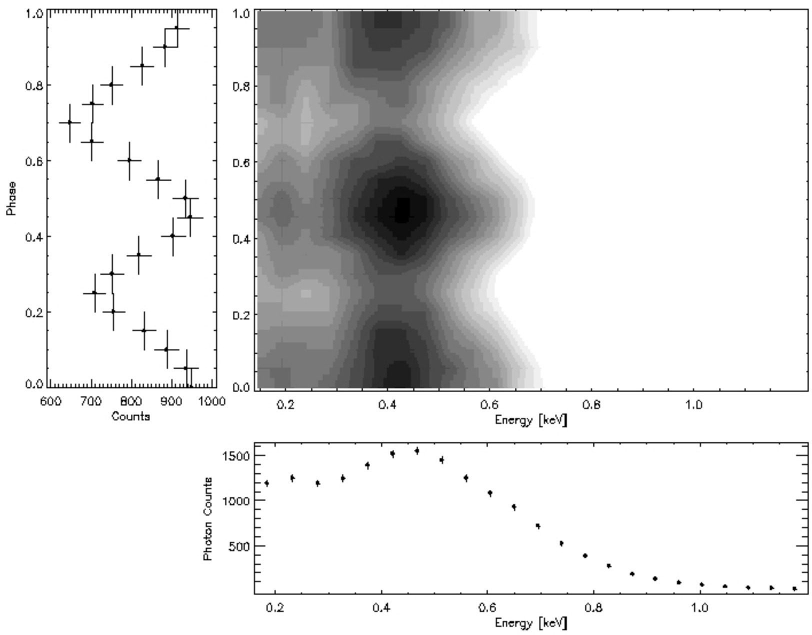

Figure 2. Energy-Phase image of RBS1223 combined from different observations. Rotational phase-folded light curve in the broad energy, 0.2-2.0 keV, band (left panel) and the phase averaged spectrum (bottom panel) are shown.

resolved spectra (i.e. energy-spin phase image, Fig. 2) of the INS RBS 1223 are satisfactorily fitted with two models, which have slightly different physical and geometrical characteristics of emitting areas. The fits show that the INS is an orthogonal rotator. The first model is parameterized by a Gaussian absorption line which is superimposed on a blackbody spectrum. The second model assumes a condensed iron surface above which there is a partially ionized, optically thin hydrogen atmosphere. Note, that the latter model is more physically motivated. We have additionally performed Markov Chain Monte Carlo (MCMC) fitting and estimated parameters and their uncertainties from posterior probability density functions.

2.2. RX J0720.4−3125

RX J0720.4−3125 is a special case among nearby thermally emitting INSs, because a clear variation in the spectrum has been detected by the *XMM-Newton* high-resolution spectral Reflection Grating Spectrometers (RGS) [15]. This detection was subsequently confirmed and analyzed by imaging-spectroscopic EPIC pn observations [3, 8] (see, e.g., Fig. 2).

Moreover, the *genuine* spin period of RX J0720.4−3125 turned out to be equal 16.78 sec (see Fig. 4) instead of 8.39 sec as reported in the literature (see, e.g., [2, 8]). Similar to the case of RBS 1223, the data from all observations of RX J0720.4−3125 conducted by *XMM-Newton*

[1] $T^4 = T^4_{\mathrm{p}1,2}\frac{\cos^2\theta}{\cos^2\theta + a_{1,2}\sin^2\theta} + T^4_{\min}$, $B = B_{\mathrm{p}1,2}\sqrt{\cos^2\theta + a_{1,2}\sin^2\theta}$, where the parameters $a_{1,2}$ are approximately equal to the squared ratio of the magnetic field strength at the equator to the field strength at the pole, $a_{1,2} \approx (B_{\mathrm{eq}}/B_{\mathrm{p}1,2})^2$. Using these parameters we can describe various temperature distributions, from strongly peaked ($a \gg 1$) to the classical dipolar ($a = 1/4$) and homogeneous ($a = 0$) ones.

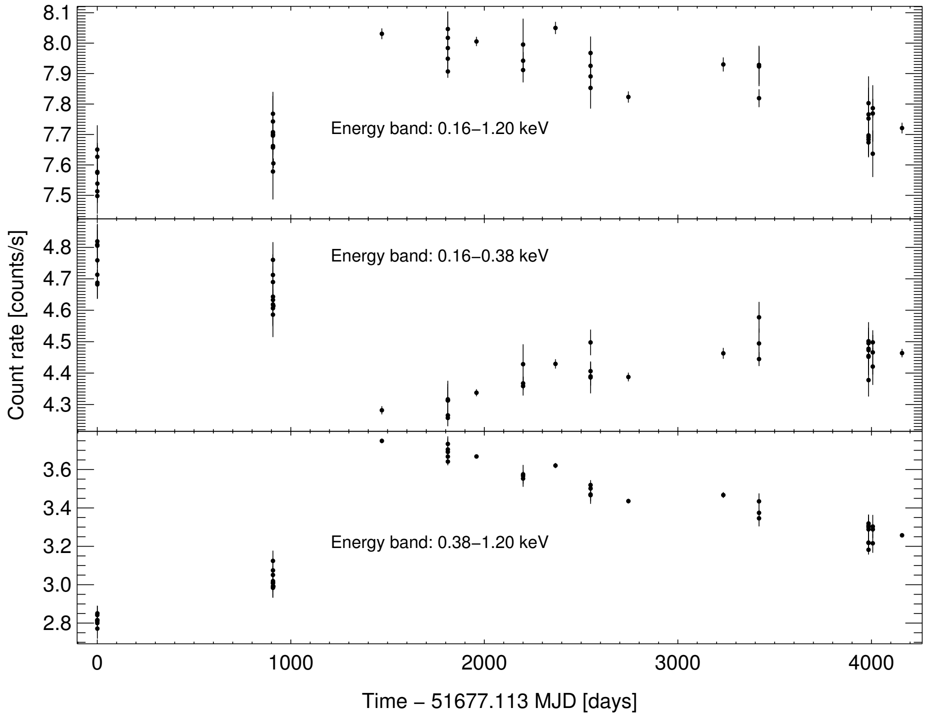

Figure 3. Observed count rates of RX J0720.4−3125 in the energy ranges 0.16−1.2 keV, 0.16−0.38 keV and 0.38−1.2 keV in different *XMM-Newton* EPIC pn observations.

EPIC pn with the same instrumental setup in 2000-2012 were reprocessed to form homogenous data set of solar barycenter corrected photon arrival times and phases were calculated according to the rotational period at that epoch. Taking into account aforementioned variations of RX J0720.4−3125 the whole data set, consisting of 16 different *XMM-Newton* pointings, was divided into five different subsets according to the brightness of the INS. Next, within each subset the spectra were co-added to form spin phase-resolved high S/N data groups and fitted simultaneously with the models described in the previous subsection. This procedure allowed us to estimate the gravitational redshift of RX J0720.4−3125, see Fig. 5.

2.3. RX J1856.5−3754

In contrary to the INSs RBS 1223 and RX J0720.4−3125, the X-ray spectrum of RX J1856.5−3754 does not show any significant absorption feature and the pulsed fraction is quite low ($\sim 1.5\%$). However, in this case there is a constraint on a viewing geometry from the observed bow-shock at this INS [10]. In addition, RX J1856.5−3754 is the nearest INS and the distance ($d = 123^{+11}_{-15}$ pc) is known with relatively good accuracy [16]. As in the previous cases of the INSs, the spin phase-resolved spectra were fitted in the same manner. The results of the estimation of gravitational redshift and therefore the compactness of this object, together with other studied INSs, are shown in Fig. 6. It is worthwhile to note that we obtained statistically acceptable fit also assuming a non-vanishing toroidal component of magnetic field of INS. This corresponds to the values of the parameter $a \gg 1$ which imply very small and hot emitting areas around the magnetic poles and yield small pulsed fraction, see footnote 1.

Nevertheless, our targeted parameter, the estimated gravitational redshift was approximately the same ($z = 0.22 \pm 0.07$, see also [7]) independent of the model. Note, also the relatively broad

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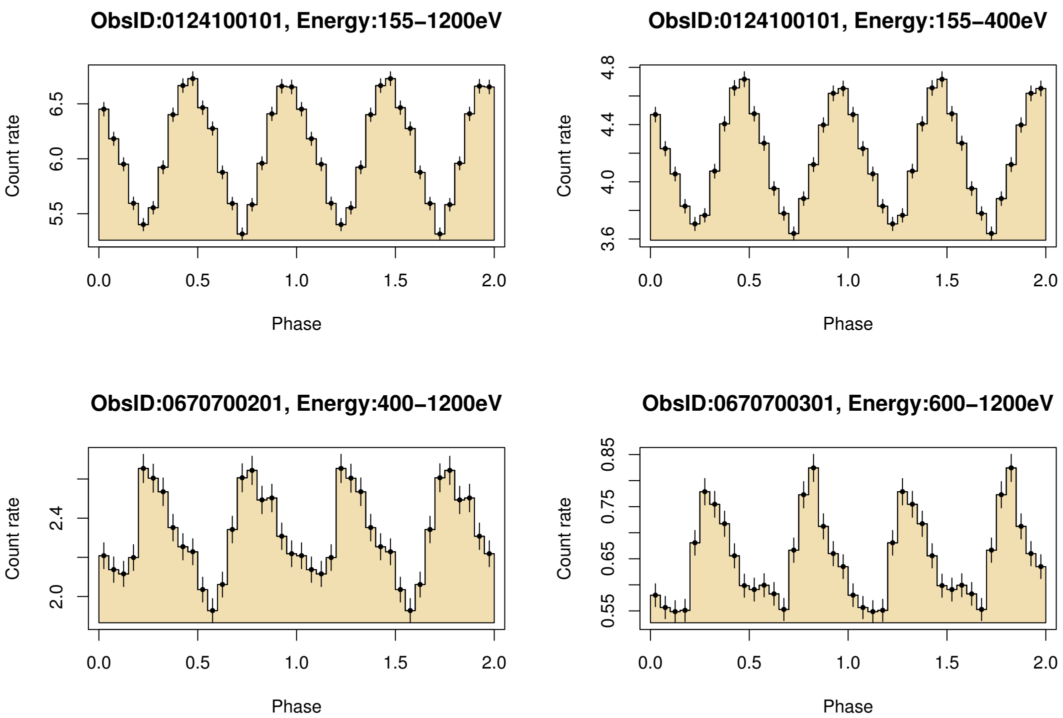

Figure 4. Phase-folded light curves with the *genuine* spin period (16.78 sec) of RX J0720.4−3125 in different *XMM-Newton* EPIC pn observations and energy bands.

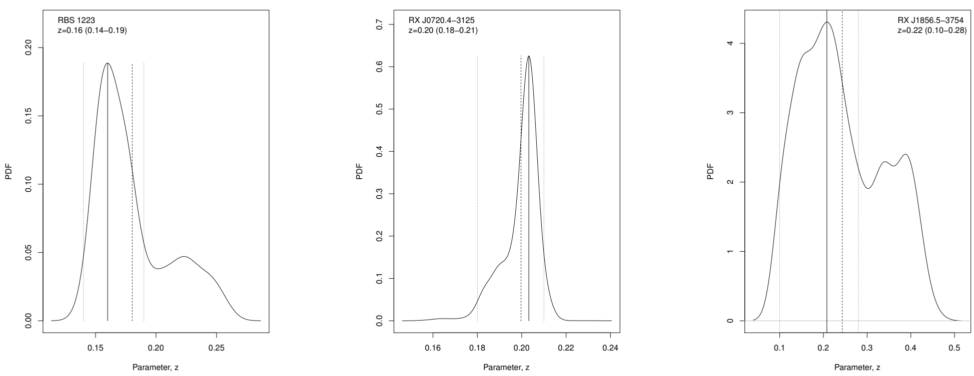

Figure 5. Probability density distribution of gravitational redshifts by Markov Chain Monte Carlo (MCMC) fitting with the model of strongly magnetized neutron star of condensed Iron surface and partially ionized Hydrogen thin atmosphere atop it for RBS 1223 (left panel), RX J0720.4−3125 (middle panel) and RX J1856.5−3754 (right panel). Dashed vertical line depicts the mean value, dotted vertical lines indicate the highest posterior probability density interval (95%).

posterior probability density function of the gravitational redshiht in comparison to the cases of RBS1223 and RX J0720.4−3125 (see Fig. 5).

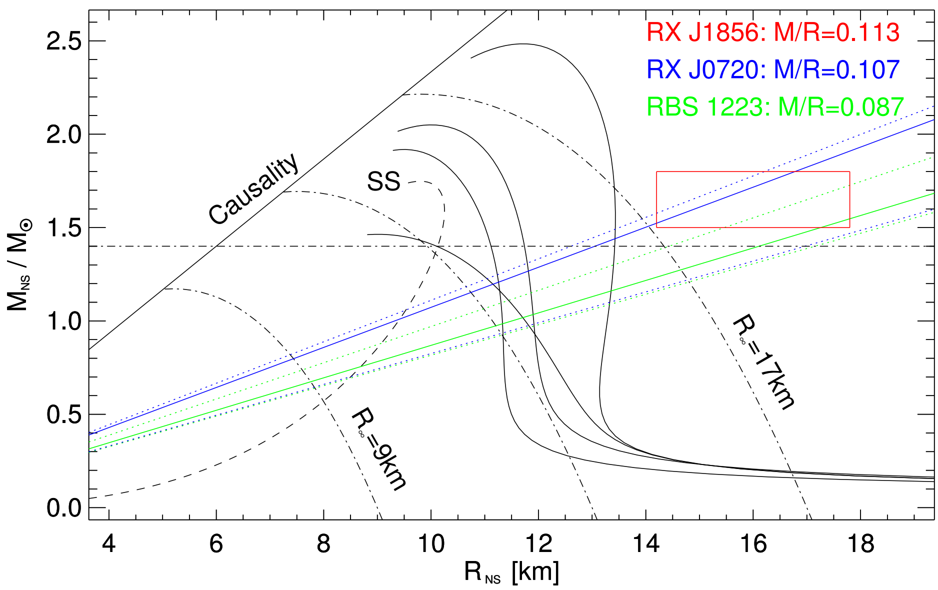

Figure 6. Mass-radius relations for several EOS ([4], thin solid curves), and a strange star (thin dash-dotted). Thick dashed: curve of constant $R^{\infty} = R/\sqrt{1-2GM/Rc^2} = 17$ km ([14].

3. Conclusions and outlook

To summarize, X-ray spin phase-resolved spectroscopic study of three thermally emitting INSs and the fit of highly magnetized atmospheric models allowed us to estimate their compactness, which are suggesting on a stiff equation of state (see, Fig. 6). More work for detailed spectral model computation will be certainly worth to do in the near future and application to the phase-resolved spectra of other INSs. In particular, analysis of the high resolution spectra observed by *XMM-Newton* and *Chandra* with possibly other absorption features [5, 11].

Acknowledgments

VH and VS acknowledge support by the German *Deutsche Forschungsgemeinschaft (DFG)* through project C7 of SFB/TR 7 “Gravitationswellenastronomie”.

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