Neutron Stars and Pulsars: Challenges and Opportunities after 80 years
Proceedings IAU Symposium No. 291, 2012
J. van Leeuwen, ed.

doi:10.1017/S1743921312024258

Constraints of the compactness of the isolated neutron stars via X-ray phase-resolved spectroscopy

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Abstract. 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 of the isolated neutron star RBS 1223. We constrain some physical properties of the X-ray emitting areas, i.e. the temperatures ($T_{pole1} \sim 105\,\mathrm{eV}, T_{pole2} \sim 99\,\mathrm{eV}$), magnetic field strengths ($B_{pole1} \approx B_{pole2} \sim 8.6 \times 10^{13}$ G) at the poles, and their distribution parameters (a1 $\sim$ 0.61, a2 $\sim$ 0.29, indicating an absence of strong toroidal magnetic field component). In addition, we are able to place some constraints on the geometry of the emerging X-ray emission and the gravitational redshift ($z \sim 0.16^{0.03}_{-0.01}$) of the isolated neutron star RBS 1223.

Keywords. stars: neutron, X-rays: stars, techniques: spectroscopic

1. Introduction

Observations and modeling of thermal emission from isolated neutron stars can provide not only information on the physical properties such as the magnetic field, temperature, and chemical composition of the regions where this radiation is produced, but also we may infer on the properties of matter at higher densities deeper inside the star.

In particular, the study of thermal emission from isolated neutron stars may allow one to infer the surface temperature and total flux measured by a distant observer and to estimate the real parameters. With the known distance and the redshifted radius of the neutron star the actual radius and mass of a neutron star are: $R = R^{\infty}[1 - 2GM/Rc^2]^{1/2}$, $M = \frac{c^2 R}{2G}[1 - (\frac{R}{R^{\infty}})^2]$ (see, e.g. Zavlin (2009)).

The detection and identification of any absorption/emission feature in the spectrum or performing rotational phase-resolved spectroscopy of isolated neutron stars will allow us to determine gravitational redshift and directly estimate the mass-to-radius ratio, M/R. Together they yield a unique solution for M and R. These spectral features may allow to measure the neutron star magnetic field and provide an important input for modeling of magnetized atmospheres.

RBS 1223 shows the highest pulsed fraction (13-42%, depending on energy band, see Fig. 1) and strongest broad absorption feature (Schwope *et al.* 2007) of all isolated neutron stars.

High quality rotation phase resolved spectroscopy is needed in order to fit with neutron star magnetized atmosphere models and to constrain the gravitational redshift of the neutron star (Suleimanov *et al.* 2010; Hambaryan *et al.* 2011).

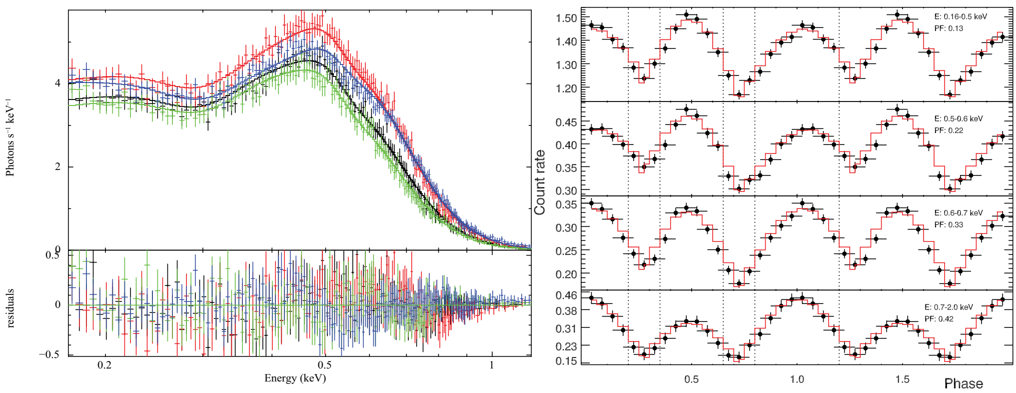

Figure 1. *XMM-Newton EPIC* pn co-added phase-averaged X-ray spectra (left panel) including primary and secondary peaks, first and second minima, and phase-folded light curves (right panel) in different energy bands of RBS 1223 combined from 12 pointed observations.

2. Data analysis and results

Using the data collected with *XMM-Newton* EPIC pn from the 12 publicly (similar instrumental setup, i.e. Full Frame, Thin1 Filter) available observations, in total presenting about 175 ks of effective exposure time, we extracted spin-phase resolved spectra with high S/N ratio (Fig. 1) and fitted simultaneously with highly magnetized isolated neutron star surface/atmosphere models (Suleimanov *et al.* 2010). These models are based on various local models and compute rotational phase dependent integral emergent spectra of isolated neutron star, using analytical approximations.

The basic model includes temperature/magnetic field distributions over isolated neutron star surface†, viewing geometry and gravitational redshift. Three local radiating surface models are also considered, namely, a naked condensed iron surface (van Adelsberg & Lai 2006) and partially ionized hydrogen model atmospheres, semi-infinite or finite atop of the iron condensed surface.

The observed phase resolved spectra (i.e. energy-spin phase image, Fig. 2) of the isolated neutron star RBS 1223 are satisfactorily fitted (verified also via MCMC, Fig. 3) with two slightly different physical and geometrical characteristics of emitting areas, a model parameterized with a Gaussian absorption line superimposed on a blackbody spectrum and by the model of a condensed iron surface, with partially ionized, optically thin hydrogen atmosphere above it, including vacuum polarization effects, as orthogonal rotator. Note, the latter one is more physically motivated. We have additionally performed Markov Chain Monte Carlo (MCMC) fitting as implemented in *XSPEC*.

The fit also suggests the absence of a strong toroidal magnetic field component. Moreover, the determined mass-radius ratio, $(M/M_{Sun})/(R/\mathrm{km}) = 0.087 \pm 0.004$, suggests a very stiff equation of state of RBS 1223.

† $T^4 = T^4_{\mathrm{p}1,2}\frac{\cos^2\theta}{\cos^2\theta + a_{1,2}\sin^2\theta} + T^4_{\mathrm{min}}, B = B_{\mathrm{p}1,2}\sqrt{\cos^2\theta + a_{1,2}\sin^2\theta}$, 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.

https://doi.org/10.1017/S1743921312024258 Published online by Cambridge University Press

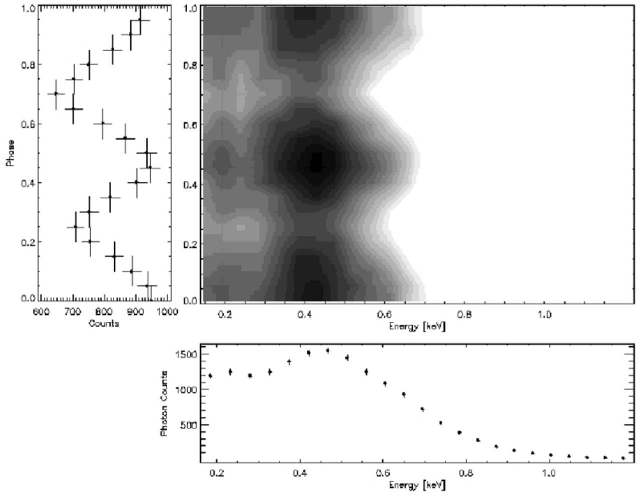

Figure 2. Energy-Phase image of RBS1223 combined from different observations. Rotational phase-folded light curve in the broad energy, 0.2-2.0 keV, band (left panel) and the phase averaged spectrum (bottom panel) are shown.

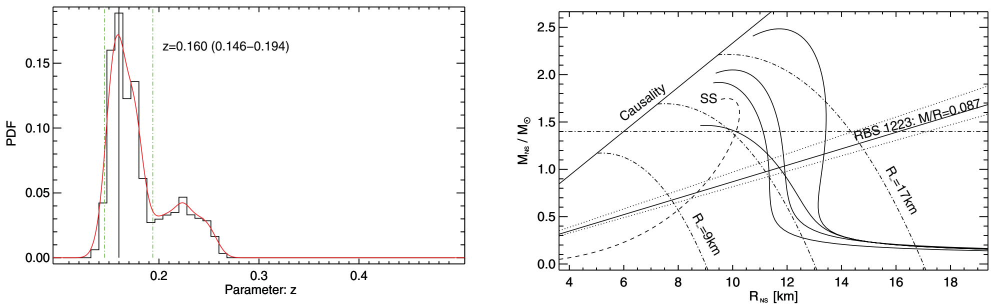

Figure 3. Probability density distribution of gravitational redshift by Markov Chain Monte Carlo (MCMC) fitting with the model of strongly magnetized neutron star condensed Iron surface and partially ionized Hydrogen thin atmosphere atop it (left panel). Dashed vertical lines indicate the highest probability interval (68%). Mass-radius relations (right panel) for several EOS (Haensel *et al.* (2007), 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 (Trümper (2005).

Acknowledgement

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

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