Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: A Borghese *et al* 2017 *J. Phys.: Conf. Ser.* **932** 012007

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Phase-dependent absorption features in X-ray spectra of X-ray Dim Isolated Neutron Stars

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Abstract. A detailed phase-resolved spectroscopy of archival *XMM–Newton* observations of X-ray Dim Isolated Neutron Stars (XDINSs) led to the discovery of narrow and strongly phase-dependent absorption features in two of these sources. The first was discovered in the X-ray spectrum of RX J0720.4-3125, followed by a new possible candidate in RX J1308.6+2127. Both spectral lines have similar properties: they are detected for only $\sim 20\%$ of the rotational cycle and appear to be stable over the timespan covered by the observations. We performed Monte Carlo simulations to test the significance of these phase-variable features and in both cases the outcome has confirmed the detection with a confidence level $> 4.6\sigma$. Because of the narrow width and the strong dependence on the pulsar rotational phase, the most likely interpretation for these spectral features is in terms of resonant proton cyclotron absorption scattering in a confined high-B structure close to the stellar surface. Within the framework of this interpretation, our results provide evidence for deviations from a pure dipole magnetic field on small scales for highly magnetized neutron stars and support the proposed scenario of XDINSs being aged magnetars, with a strong non-dipolar crustal B-field component.

1. Introduction

The XDINSs form a group of seven thermally-emitting, radio-quiet [1], nearby ($\lesssim 500\,\mathrm{pc}$) X-ray pulsars, originally discovered by *ROSAT* (see [2] for a review). Timing studies have shown that XDINSs are slow rotators with periods in the range $3-12\,\mathrm{s}$ and spin down regularly with period derivatives of the order of $10^{-14}-10^{-13}\,\mathrm{s\,s^{-1}}$ [3]. The inferred surface dipolar magnetic field is typically of the order of $10^{13}\,\mathrm{G}$, being close to the magnetar ones. Their X-ray luminosity, $\approx 10^{31-32}\,\mathrm{erg\,s^{-1}}$, exceeds the spin-down luminosity making XDINSs different from the rotation-powered pulsars.

XDINSs appear to be thermally cooling with emission in the soft X-ray band and faint optical and/or ultraviolet counterparts [4]. This thermal emission is thought to be due to residual heat and to come directly from the stellar surface. XDINSs show thermal spectra which can be well described by blackbody models with inferred temperature in the range $kT \sim 50-100\,\mathrm{eV}$. In the past decades *XMM–Newton* observations have detected deviations from a pure blackbody model in six of the XDINSs, in the form of broad absorption features in the phase-averaged spectra. Their origin is still an open issue: they could be due to proton cyclotron resonances/atomic transitions in a magnetized atmosphere [5] or to an inhomogeneous surface temperature distribution [6].

Recently, phase-dependent features have been observed in two low-field magnetars, SGR 0418+5729 [7] and Swift J1822.3-1606 [8]. These findings have motivated our search for similar features in the XDINS sample. According to the most recent magneto-thermal evolution models [9], XDINSs are thought to be descendants of magnetars, therefore we expect to find such phase-dependent features in their X-ray spectra.

In this proceeding we summarise the discoveries published in Borghese et al. [10, 11]. Moreover, we present additional results for RX J0720.4-3125; in particular, we repeated our analysis assuming the new rotational period recently proposed by Hambaryan et al. [12].

2. Observations and data analysis

We re-analysed all the available *XMM–Newton* observations of the XDINSs, focusing on the data acquired by the EPIC pn camera which provides the spectra with the highest counting statistics owing to its larger effective area than the MOS cameras. The raw data were processed following the standard threads from the Science Analysis Software (see Borghese et al. [10, 11] for details about the data reduction, the observation logs and the timing solutions).

To study spectral variations as a function of the rotational phase without making assumptions about the spectral energy distribution, normalized energy versus phase images were created by binning the source counts in rotational phase and energy bins, and then normalizing to the phase-averaged spectrum and pulse profile. We found possible candidates in RX J0720.4-3125 and RX J1308.6+2127 : the images (fig. 1) exhibit features in a narrow phase interval, which are produced by the lack of counts with respect to the nearby energy channels. These might correspond to absorption spectral lines present in a limited interval of the rotational phase. To further investigate the presence of these features we performed a detailed phase-resolved spectral analysis by dividing the rotational phase in bins and extracting the corresponding spectra.

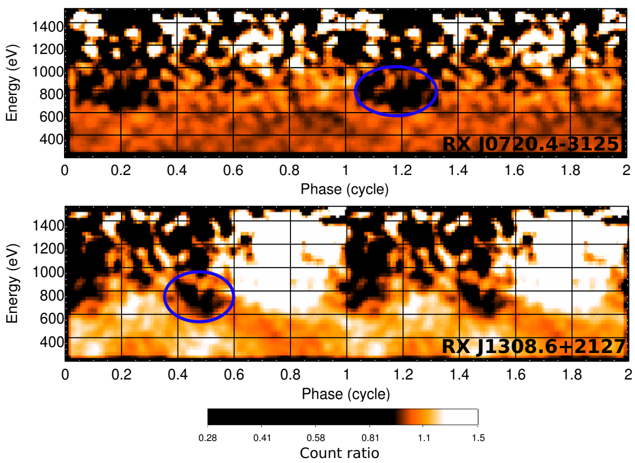

Figure 1. Normalized energy versus phase images for the longest *XMM–Newton* observations of RX J0720.4-3125 (top, 51 ks, folded on a period of 8.39 s) and RX J1308.6+2127 (bottom, 35.1 ks, folded on a period of 10.31 s) obtained by binning EPIC pn source counts into 100 phase bins and 25-eV-wide energy channels. The blue ellipses mark the phase-dependent features. Two cycles are shown for better visualization.

2.1. RX J0720.4-3125

RX J0720.4-3125 was discovered as an isolated, pulsating neutron star with a spin period of 8.39 s [13]. The phase-averaged spectrum is well modelled by a blackbody with temperature $kT_{BB} \sim 85$ eV and the inclusion of a broad absorption feature ($E_{line} \sim 270$ eV, $\sigma \sim 70$ eV) [14]. Hambaryan et al. (2017) claimed a new rotational period, which is twice that reported in

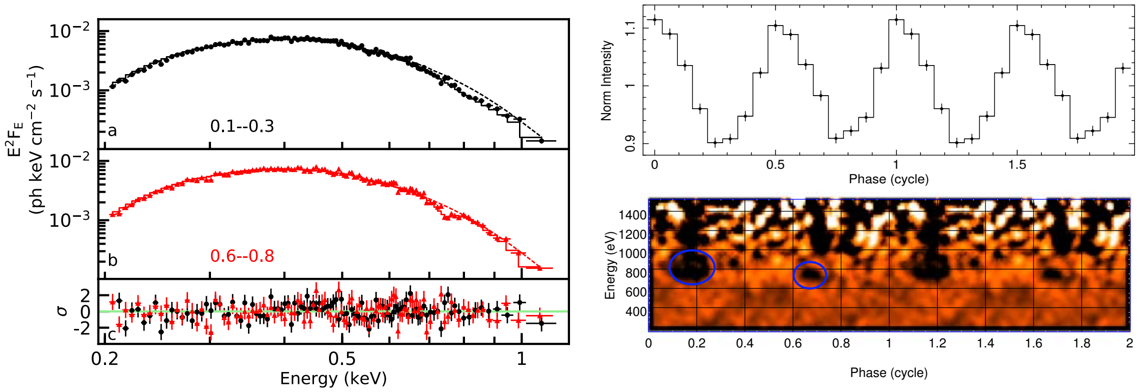

Figure 2. Results for RX J0720.4-3125 using the new period of ~ 16 s, for the observation performed on 2nd May 2003 (51 ks). Left-hand, panel a: 0.1 – 0.3 phase-resolved spectrum fitted with an absorbed blackbody plus a Gaussian profile (solid line). The dashed line represents the blackbody component. Left-hand, panel b: 0.6 – 0.8 phase-resolved spectrum fitted with an absorbed blackbody plus a Gaussian profile (solid line). The dashed line represents the blackbody component. Left-hand, panel c: residuals with respect to the best-fitting models. Right-hand panel, top: light curve folded on the period 16.78 s and sampled in 16 phase bins. Right-hand panel, bottom: normalized energy versus phase image using the above-mentioned period; for the colour scale see fig. 1. The blue ellipses mark the narrow features. Two cycles are shown for better visualization.

literature. We performed our analysis assuming a period of 8.38 s (see fig. 1, top panel and [11]) and of 16.78 s, for which we report our results here (fig. 2).

XMM–Newton observed RX J0720.4-3125 twenty times between May 2000 and September 2012. We started our analysis from the longest observation (51 ks) performed on 2nd May 2003. We fitted the phase-averaged spectrum with an absorbed blackbody model in the energy range 0.3 – 1.2 keV (excluding the broad absorption feature in order to reduce the degrees of freedom). The corresponding phase versus energy image gives us a hint for a narrow spectral line in the phase bin 0.1 – 0.3 if we fold the light curve with a period of ~ 8 s (fig. 1, top panel); using the new period, the feature appears in two phase intervals, 0.1 – 0.3 and 0.6 – 0.8 (fig. 2, right-hand panel). For the spectrum relative to these phases, the addition of a Gaussian line in absorption to the blackbody continuum leads to an improvement in the residuals, whereas a simple blackbody model gives an acceptable fit for all the other phase intervals. Considering the case of the new period, the spectral feature has consistent energies within the errors (90% confidence level), ~ 740 eV, while it shows different widths σ and equivalent widths EqW. For the 0.1 – 0.3 phase-resolved spectrum the line is broader and deeper ($\sigma \sim 43$ eV and $EqW \sim 44$ eV), while we obtained an upper limit for the width of ~ 62 eV and an EqW of ~ 19 eV for the feature in the 0.6 – 0.8 phase bin.

2.2. RX J1308.6+2127

RX J1308.6+2127 was identified as a possible nearby isolated neutron star rotating at 10.31 s in the *ROSAT* Bright Survey [15]. The phase-averaged spectrum is fitted with a combination of an absorbed blackbody ($kT_{BB} \sim 85$ eV) and a Gaussian absorption line ($E_{line} \sim 270$ eV, $\sigma \sim 155$ eV) with the largest equivalent width (~ 180 eV) in the XDINS sample [16].

Thirteen observations were carried out by *XMM–Newton* between December 2001 and June 2007; we excluded observations with an exposure time less than 10 ks (because of insufficient statistics) and merged together those performed within a month, focusing on six data sets in total. For each of them the normalized images display an additional narrow feature in certain rotational phases, 0 – 0.2 and 0.4 – 0.6 (see fig. 1, bottom panel for the longest observation, and [10]). To fit the six phase-resolved spectra simultaneously, we used a combination of an absorbed blackbody with an absorption line for the phase-averaged feature. Because of a dependence of the phase-averaged feature energy on the rotational phase [16], we allowed this parameter to vary for the different phase-resolved spectra. As shown in figure 3 panel b, the residuals in the spectra relative to 0.4 – 0.6 phase bin reveal a discrepancy between the model and the data around ~ 0.7 keV, which is less prominent in the 0 – 0.2 phase-resolved spectra. The inclusion of a Gaussian line in absorption improves the residual shape especially for the 0.4 – 0.6 phase-resolved spectra (see panel c). The feature has an energy of ~ 740 eV and an equivalent width of ~ 15 eV, the width is compatible with the spectral energy resolution of the pn camera.

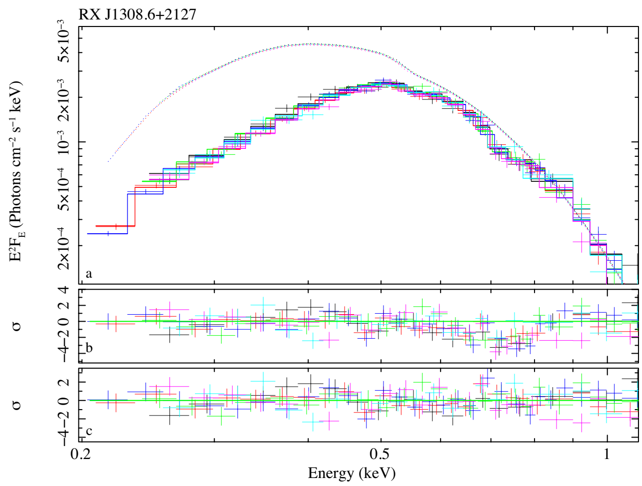

Figure 3. Results for RX J1308.6+2127. Panel a: the unfolded 0.4 – 0.6 phase-resolved spectra from six different observations considered in the analysis fitted simultaneously. The solid line represents the best-fitting model (an absorbed blackbody plus two absorption Gaussian lines), while the dashed line is the blackbody component. Panel b: residuals after setting the normalization of the phase-dependent line to zero. Panel c: residuals with respect to the best-fitting model.

2.3. Upper limits for other XDINSs

For the other sources in the sample (RX J1856.5-3754, RX J1605.3+3249, RX J2143.0+0654, RX J0806.4-4123, RX J0420.0-5022) no features have been observed in the normalized images. For the phase-averaged spectrum of the longest observation we derived 3σ upper limits on the equivalent width of a Gaussian line in absorption with a width of 0 eV (i.e. compatible with the energy resolution of the pn camera) and of 100 eV (for more details see [10]).

3. Significance of the features

To test the significance of the phase-dependent narrow spectral features detected in RX J0720.4-3125 and RX J1308.6+2127 we performed Monte Carlo simulations [17]. In both cases we simulated 10^5 spectra based on the model for the phase-averaged spectrum (the null model) and fitted them with an alternative model, i.e. including a narrow Gaussian line in absorption to account for the phase-dependent feature. In none of the simulated spectra the feature has an equivalent width higher than the observed value for both sources. Therefore the probability of the features being a fluctuation is $< 10^{-5}$. This value can be interpreted as a p-value. The outcome of the simulations relies on the assumption that the null model is true, so a p-value $< 10^{-5}$ means that the features are unlikely to have occurred by chance if the null model holds. A p-value $< 10^{-5}$ corresponds to a confidence level $> 4.6\sigma$, supporting thus our detections (for further details see [10]).

4. Discussion

A visual inspection of the normalized energy versus phase images gave us a hint for phase-dependent features in the spectra of two XDINSs, RX J0720.4-3125 and RX J1308.6+2127. Their presence was confirmed thanks to a detailed phase-resolved spectral analysis and Monte Carlo simulations. In both sources the spectral lines are detected in a limited phase interval ($\sim$ 1/5 of the rotational cycle). They have an energy of ~ 750 eV and width consistent with the spectral resolution of the pn camera. Interestingly similar features have been detected in two low-B magnetars, SGR 0418+5729 [7] and Swift J1822.3-1606 [8]; in these cases the line energy is higher (> 2 keV) and shows a stronger variation in phase. These discoveries strengthen the evolutionary connection between magnetars and XDINSs, considered to be aged magnetars.

The similarities between the features in the two different classes suggest that the same mechanism might be at work in both cases: the features might be explained invoking proton cyclotron resonant absorption scattering in a confined magnetic loop close to the star surface [7]. The proton cyclotron energy measured by a distant observer is $E_{\rm c} = (eB\hbar/m_{\rm p})/(1+z) = 0.63B_{14}/(1+z)$ keV, where $B_{14} = B/10^{14}$ G, $z = 2GM_{\rm NS}/R_{\rm NS}c^2 \sim 0.4$ (assuming a neutron star mass $M_{\rm NS} = 1.4M_\odot$ and a radius $R_{\rm NS} = 10$ km) and $1+z$ is the gravitational redshift. The implied magnetic field in the loop is then $B_{\rm loop} \sim 2 \times 10^{14}$ G, higher than the dipolar magnetic field at the equator ($B_{\rm dip} \sim 2.5 \times 10^{13}$ G and $\sim 3.4 \times 10^{13}$ G for RX J0720.4-3125 [18] and RX J1308.6+2127, [19] respectively).

Atomic transitions in a magnetized atmosphere is an alternative explanation; however, current atmosphere models cannot successfully describe the spectra. Moreover the line energy is too high to be explained by transitions in light element atoms. The strong dependence on the rotational phase requires that the atmosphere is on top of a small part of the surface, while the primary emission comes from a larger region, but it is difficult to understand how only a small part of the surface can be covered by some absorbing material. Therefore, the first interpretation is preferred and, if confirmed, supports the scenario according to which the magnetic field of highly magnetized neutron stars is more complex than a pure dipole on small scale, with localized high B-field bundles.

5. Conclusions

A careful re-analysis of archival *XMM–Newton* EPIC pn data allowed us to discover phase-dependent features in the X-ray spectra of RX J0720.4-3125 and RX J1308.6+2127, and to derive upper limits for the other XDINSs. The properties of the features are naturally explained in the proton cyclotron scattering scenario if localized magnetic field bundles are present close to the surface of the star. Moreover, these discoveries provide important implications on the evolutionary link between magnetars and XDINSs.

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