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Deep eROSITA observations of the *magnificent seven* isolated neutron stars

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Abstract. We report the initial results of deep eROSITA monitoring of the *magnificent seven* isolated neutron stars (INSs). Thanks to a combination of high count statistics and good energy resolution, the eROSITA datasets unveil the increasingly complex energy distribution of these presumably simple thermal emitters. For three targets, we report the detection of multiple (in some cases, phase-dependent) spectral absorption features and deviations from the dominant thermal continuum. Unexpected long-term changes of spectral state and timing behaviour have additionally been observed for two INSs. The results pose challenging theoretical questions on the nature of the variations and absorption features and ultimately impact the modeling of the atmosphere and cooling of highly magnetised neutron stars.

Keywords. surveys, stars: neutron, X-rays: individual (RX J0720.4-3125, RX J1605.3+3249, RX J2143.0+0654)

1. The *magnificent seven* isolated neutron stars

A major outcome of the ROSAT mission was the discovery of a group of seven nearby radio-quiet isolated neutron stars (INSs; e.g. Turolla 2009; Haberl 2007). The sources, dubbed the *magnificent seven* (M7), have been regarded as the closest-to-perfect candidates for testing neutron star emission and cooling models, based on a combination of bright thermal emission, proximity, independent distance estimates, and lack of significant magnetospheric or accretion activity (Potekhin 2014). Relative to standard (spin-powered) pulsars, the M7 rotate more slowly, show higher thermal X-ray luminosity compared to the spin-down power, and have higher inferred magnetic field intensities. These properties suggest that additional heating of the neutron star crust may have been at work by means of field decay, implying an evolutionary link with magnetars (e.g. Borghese; these proceedings). The M7 INSs are routinely observed by eROSITA, the primary X-ray telescope on-board the SRG Observatory (Predehl et al. 2021). Moreover, SRG/eROSITA has just successfully completed half of its planned four-year all-sky survey mission: by the time it reaches final depth in late 2023, dedicated identification campaigns for new INS candidates can increase the observed population by significant factors (Kurpas et al.; these proceedings).

2. Overview of the eROSITA observations

In the circa two years between first light in October 2019 and the time of this symposium, eROSITA targeted the M7 INSs RX J0720.4-3125, RX J2143.0+0654 and RX J1605.3+3249 in eight occasions. In addition, the prototype of the group, RX J1856.6-3754, was observed three times for cross-calibration purposes with the Chandra LETG HRC-S instrument; these results will be reported elsewhere. In Table 1 is an overview

Table 1. SRG/eROSITA observations of three of the M7 INSs.

Target ID **RX**	***obsid***	**Observation Date**	**Net Exposure [s]**	**GTI [%]**	**Counts [$\times 10^5$]**	**Rate [s^{-1}]**	**Remark**
(1) J0720	700007	2019-10-16	87810	87	8.176(15)	9.4692(17)	XMM TOO
(2) J2143	700198	2019-12-02	54650	99	1.622(3)	2.979(5)	$p_f = 2.46(24)\,\%$
	720005	2020-11-25	55390	93	1.059(3)	2.822(8)	$p_f = 1.9(3)\,\%$
	730031	2021-05-25	49400	85	1.434(3)	2.903(5)	$p_f = 2.72(26)\,\%$
	740005	2021-11-25	50400	70	0.952(3)	2.806(9)	$p_f = 2.1(3)\,\%$
(3) J1605	720000	2020-08-06	32360	56	1.791(3)	5.585(10)	∼ AO11–AO14
	730000	2021-03-07	59460	83	3.136(3)	5.380(6)	Spectral change
	740001	2021-09-07	54610	83	1.885(3)	5.051(9)	Intermediate state

Table 2. Results of the spectral analysis. The observations of Table 1 are fitted simultaneously with high-quality EPIC pn exposures of each target. In (3) the uncoupled $kT_{\rm BB}$, $R_{\rm BB}$ parameters are $105.2^{+1.8}_{-3}$ eV, $0.74^{+0.4}_{-0.26}$ km (March 2021), and $102.3^{+2.4}_{-2.8}$ eV, $0.9^{+0.4}_{-0.3}$ km (September 2021).

	$N_{\rm H,20}$	$kT_{\rm BB}^{\rm cool}$	$R_{\rm BB}^{\rm cool}$	$kT_{\rm BB}$	$R_{\rm BB}$	ϵ_1	σ_1	ϵ_2	σ_2	ϵ_3	σ_3
	[$\rm cm^{-2}$]	[eV]	[km]	[eV]	[km]	[eV]					
(1)	7.4(5)			$85.9^{+0.4}_{-0.3}$	5.5(1.0)	359^{+7}_{-9}	63^{+9}_{-8}	548^{+4}_{-7}	< 17	770^{+8}_{-7}	35^{+14}_{-13}
(2)	$13.2^{+0.8}_{-0.9}$	$43.0^{+3}_{-2.0}$	< 90	$107.4^{+3}_{-2.8}$	0.6(3)	392(3)	86(6)	548^{+6}_{-5}	50^{+13}_{-8}	735(6)	32^{+13}_{-10}
(3)	5.4(4)	$35.9^{+1.9}_{-1.3}$	28^{+21}_{-18}	$100.4^{+1.1}_{-1.2}$	$0.96^{+0.3}_{-0.29}$	443^{+7}_{-8}	77^{+9}_{-10}	557(6)	36(8)	845^{+8}_{-12}	133^{+6}_{-13}

of the eROSITA datasets. All observations were analysed with *eSASS* version 201009, pipeline processing c001, following standard procedures. The net exposures and percentages of good-time-intervals (GTIs) in Table 1 are averaged over all active telescope modules; total photons and count rates are in the $0.2 - 1.5$ keV energy band. For details on the reduction and spectral analysis of eROSITA data we refer to Schwope et al. 2021.

3. Results and outlook

The results of phenomenological spectral models are summarised in Table 2; more physically motivated neutron star atmospheres will be investigated elsewhere. We show for each target (IDs as in Table 1) the best-fit column density in units of $10^{20}\,\rm cm^{-2}$ ($N_{\rm H,20}$), the temperature $kT_{\rm BB}$ and size of the emission region $R_{\rm BB}$ of the main (eventually, "cool") blackbody components, and the energy ϵ and width σ of Gaussian absorption features. The emitting areas are normalised to 300 pc for RX J0720.4-3125 and 100 pc for RX J2143.0+0654 and RX J1605.3+3249. For the fit results in (3), $kT_{\rm BB}$ and $R_{\rm BB}$ of the hot blackbody component, as well as the strength of the absorption features (not shown in Table 2), are uncoupled while fitting the spectra of the different epochs together.

3.1. *RX J0720.4-3125*

Thus far an outlier, the INS is well known to display long-term variability. This behaviour has been interpreted as possibly cyclic and related to the star precession, or caused by an accretion or glitch episode (Haberl et al. 2006; van Kerkwijk et al. 2007). Coordinated eROSITA/XMM-Newton observations were performed in October 2019. The joint analysis of the observations shows evidence for three absorption features, with energies and properties seemingly consistent with those of previous results reported in the literature (Hambaryan et al. 2009; Borghese et al. 2015). The dependence of the features with respect to the INS spin is under investigation by means of phase-resolved spectroscopy.

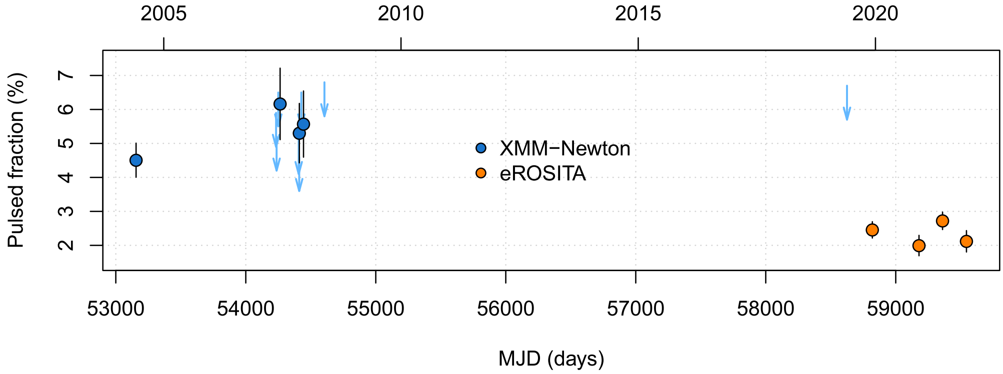

Figure 1. Long-term variation of pulsed fraction observed for RX J2143.0+0654.

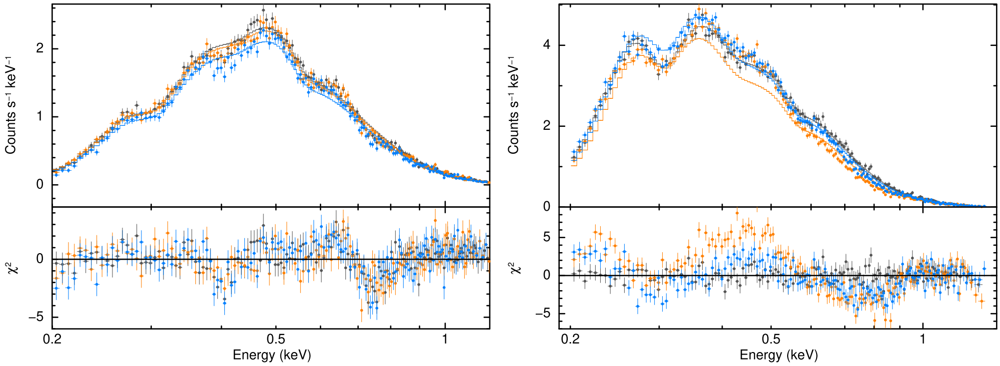

Figure 2. eROSITA spectra of RX J2143.0+0654 (*left*) and RX J1605.3+3249 (*right*), where we highlight the spectral changes undergone by the latter and absorption features detected in the spectra of the former. Three epochs are shown for each target (see the text for details).

3.2. *RX J2143.0+0654*

The source appears particularly hot in X-rays and bright in the optical/UV (Kaplan et al. 2011); it may also be the most magnetised in the group if the broad spectral absorption feature at ∼ 0.75 keV is interpreted as a proton cyclotron line (Zane et al. 2005). A recent XMM-Newton observation performed in May 2019 failed to detect the smooth flux modulation of the neutron star, previously measured at the 4.5% level (cf. detections and upper limits in Fig. 1). The decrease in pulsed fraction (p_f) is confirmed by four much deeper eROSITA observations, which recover the INS modulation at about the 2.5% level (Table 1). Moreover, the INS spin is consistently registered in all epochs at a lower frequency than expected from the putative timing solution of Kaplan and van Kerkwijk 2009: this suggests that the neutron star undergoes a stronger braking than previously thought. The analysis of the eROSITA spectra (Fig. 2; *left*) reavealed two additional absorption features and evidence of a colder thermal component (Table 2; see also Schwope et al. 2009). Despite the variations in timing behaviour, we measured no significant changes in flux or spectral state over 17 years.

3.3. *RX J1605.3+3249*

We have recently investigated the INS with XMM-Newton (Pires et al. 2019, 2014). While the results of a first (August 2020) eROSITA observation are consistent with those of the AO11–AO14 campaigns, in a second observation, conducted seven months later, the source shows very significant variations in its spectral state (cf. orange as opposed to the dark grey flat residuals in Fig. 2; *right*). The changes can be described by an increase of temperature and decrease of size of the emitting region of the main (hot) blackbody component (see the caption of Table 2), accompanied by an overall 5% decrease in source flux. In addition to the broad feature at 0.4 keV, other deviations from the thermal continuum are observed, in particular a prominent absorption at 0.8 keV (cf. previous reports in Haberl 2007; Pires et al. 2014). The variations are confirmed by an XMM-Newton TOO performed in July 2021 (F. Haberl, priv. comm.). A third eROSITA observation from September 2021 indicates that the source is gradually returning to its previous state (blue in Fig. 2; *right*). Interestingly, Pires et al. 2019 reported a low-significance temporal trend on the parameters of the source in the analysis of RGS data dating back to 2002.

3.4. *Outlook*

Up to now, the M7 have been considered a unique group of cooling neutron stars, sharing a rather stable and well-defined set of properties. The long-term variations observed for now three sources challenge this perception: monitoring of their timing and spectral behaviour will allow the investigation of possible scenarios and the physical mechanisms behind the changes. Forthcoming calibration improvements will likewise help us better determine the column density towards the sources and the properties of the (broad and narrow, spin-dependent) absorption features, which are crucial to tackle their origin. Overall, the first two years of the mission have led to exciting results; we expect eROSITA's contribution to be paramount not only regarding population properties but also for the modeling of the atmosphere and thermal evolution of highly magnetised neutron stars.

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