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The continued spectral and temporal evolution of RX J0720.4–3125

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ABSTRACT

RX J0720.4–3125 is the most peculiar object among a group of seven isolated X-ray pulsars (the so-called Magnificent Seven), since it shows long-term variations of its spectral and temporal properties on time-scales of years. This behaviour was explained by different authors either by free precession (with a 7 or 14 yr period) or possibly a glitch that occurred around $\text{MJD} = 528\,66 \pm 73$ d.

We analysed our most recent *XMM–Newton* and *Chandra* observations in order to further monitor the behaviour of this neutron star. With the new data sets, the timing behaviour of RX J0720.4–3125 suggests a single (sudden) event (e.g. a glitch) rather than a cyclic pattern as expected by free precession. The spectral parameters changed significantly around the proposed glitch time, but more gradual variations occurred already before the (putative) event. Since $\text{MJD} \approx 530\,00$ d the spectra indicate a very slow cooling by ~ 2 eV over 7 yr.

Key words: stars: neutron – pulsars: individual: RX J0720.4–3125.

1 INTRODUCTION

The isolated neutron star (NS) RX J0720.4–3125 (RX J0720) belongs to a group of seven nearby ($\lesssim 500$ pc) radio-quiet X-ray pulsars, the so-called Magnificent Seven (M7), discovered as bright X-ray sources in the *ROSAT* all-sky survey data. The M7 exhibit soft ($T_{\text{eff}} \approx 40$ – 100 eV) blackbody-like X-ray spectra, in some cases with one or more broad absorption features that are interpreted as proton–cyclotron resonances or atomic transitions of bound species in a strong magnetic field, $B \approx 10^{13}$ – 10^{14} G. Assuming magnetic dipole braking, similar magnetic field strengths can be derived from the standard spin-down formula for those sources for which pulse periods (all in the 3–12 s interval) and period derivatives are measured (see van Kerkwijk & Kaplan 2008; Kaplan & van Kerkwijk 2009a,b). The M7 have ages of 0.3–3 Myr, as inferred by cooling curves or kinematics (Kaplan, van Kerkwijk & Anderson 2002; Tetzlaff et al. 2010), while the characteristic ages are larger (2–5 Myr). For a detailed review of the M7, we refer to Haberl (2007) and Kaplan & van Kerkwijk (2009a).

RX J0720 is the second brightest member of the M7 and it was identified as a pulsating X-ray source with an 8.39 s spin period in

Haberl et al. (1997). Cropper et al. (2001) discovered a hardness ratio variation with pulse phase and a phase shift between the flux and the hardness ratio in the *XMM–Newton* data of RX J0720. Based on *XMM–Newton* RGS data, de Vries et al. (2004) showed that the energy-dependent change in the pulse profile is accompanied by a long-term change of the X-ray spectrum.¹ The spectral changes were soon confirmed using *XMM–Newton* EPIC (Haberl et al. 2004) and *Chandra* LETG-Sdata (Vink et al. 2004). Furthermore, Haberl et al. (2006) found a phase lag between soft (0.12–0.40 keV) and hard (0.40–1.00 keV) photons, which changed over years. The *XMM–Newton* spectra of RX J0720 are best modelled with a blackbody plus a broad absorption feature at ~ 0.3 keV (Haberl et al. 2004). Haberl et al. (2006) reported variations of the blackbody temperature, the equivalent width (EW) of the absorption feature and the blackbody normalization of RX J0720 compatible with a periodic behaviour with a long-term period of $P_{\text{long}} \approx 7.1$ yr. However, the data used in Haberl et al. (2006) spanned only 4.5 yr, i.e. not the complete cycle of the tentative period.

¹ Note that initially the changes at longer wavelengths were overestimated, as the *XMM–Newton* RGS instrument suffers from a decline in sensitivity in the long-wavelength band.

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Table 1. The three new *XMM–Newton* observations (all with a thin filter) performed after Hohle et al. (2010). We list the net counts in soft band (0.12–0.40 keV) and hard band (0.40–1.00 keV). The soft photons from the EPIC-MOS data are not used in this work.

MJD (d)/ Observation ID	EPIC/setup	effective exposure (ks)	Net counts (soft)	Net counts (hard)
55 662/ 0650920101	pn/FF MOS1/SW MOS2/SW	14.41 20.47 19.86	53 014 – –	38 114 10 429 10 260
55 684/ 0670700201	pn/FF MOS1/SW MOS2/SW	13.10 22.02 23.20	48 680 – –	35 436 11 934 12 224
55 835/ 0670700301	pn/FF MOS1/SW MOS2/SW	22.18 25.82 25.83	86 713 – –	58 888 12 975 13 042

The period derivative of RX J0720 was first estimated by Zane et al. (2002) and subsequently further constrained by Cropper et al. (2004) and Kaplan & van Kerkwijk (2005) as new observations became available. Haberl et al. (2006) found that periodical phase residuals were possibly present (again with $P_{\text{long}} \approx 7.5$ yr) in the timing solution of RX J0720 with a constant value of $\dot{P} = 0.698(2) \times 10^{-13} \text{ s s}^{-1}$ (Kaplan & van Kerkwijk 2005).

The spectral and temporal variations of RX J0720 are unique among the M7 and were explained either by free precession (Haberl et al. 2006; Haberl 2007; Hohle et al. 2009), or a glitch that occurred at MJD = $528\,66 \pm 73$ d (van Kerkwijk et al. 2007). Both scenarios, free precession and the glitch event, have their drawbacks, as

discussed in van Kerkwijk et al. (2007) and Hohle et al. (2009, 2010).

The most recent overview of the spectral evolution of RX J0720 was given in Hohle et al. (2009). Since then, our team performed five further *XMM–Newton* observations. Moreover, three *Chandra* observations were obtained after the last update of the timing solution (Hohle et al. 2010). Here, we present our analysis and results for these more recent data sets in connection with further spectral and temporal evolution of RX J0720.

2 DATA AND DATA REDUCTION

In addition to Hohle et al. (2009) we analyse here five new *XMM–Newton* observations, two of which (revolutions 1700 and 1792) were already used for the timing in Hohle et al. (2010), but not for investigating the spectral behaviour. We reduced all available *XMM–Newton* data of RX J0720 with the standard *XMM–Newton* Science Analysis System version 11.0 using the EPCHAIN and EMCHAIN tasks for EPIC-pn (Strüder et al. 2001) and EPIC-MOS (Turner et al. 2001), respectively. For details on the analysis of the *XMM–Newton* data (i.e. data extraction and good time interval filtering) we refer to Hohle et al. (2009, 2010, 2012). We list the three new data sets (neither used for timing, nor for spectroscopy so far) in Table 1. EPIC-MOS was always used in small window (SW) mode with a time resolution of 0.3 s, whereas EPIC-pn was used in full frame (FF) mode (time resolution of 73.4 ms).

We analysed the *Chandra* HRC-S/LETG (Juda 1996) data with EMCHAIN and referred to Hohle et al. (2010, 2012) for details, both on the data reduction and the most recent *Chandra* HRC-S/LETG observations (SRON and MPE guaranteed time data) of RX J0720.

Table 2. Effective temperature (kT) and radiation radius (both measured at infinity), flux and EW of the broad absorption feature derived from *XMM–Newton* EPIC-pn spectra (see also Fig. 1). All observations were performed in FF mode with a thin filter, except revolution 0175 (medium filter) and revolution 0711 (SW mode with a medium filter), which are highlighted in italic. All errors denote 90 per cent confidence level.

Revolution No.	MJD (d)	kT (eV)	Radius (km)	EW (eV)	Flux 0.12–1.0 keV ($10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$)
0078	516 77	84.74 ± 0.43	$5.33^{+0.10}_{-0.10}$	$-8.9^{+3.8}_{-3.9}$	$1.0903^{+0.0094}_{-0.0100}$
<i>0175</i>	<i>518 70</i>	84.32 ± 0.57	$5.38^{+0.13}_{-0.14}$	$-7.9^{+2.9}_{-6.1}$	$1.1061^{+0.0062}_{-0.0062}$
0533	525 85	87.01 ± 0.57	$5.08^{+0.12}_{-0.12}$	$-17.2^{+5.0}_{-5.1}$	$1.0914^{+0.0092}_{-0.0108}$
0534	525 87	86.63 ± 0.48	$5.13^{+0.10}_{-0.10}$	$-20.7^{+4.0}_{-4.3}$	$1.0800^{+0.0060}_{-0.0080}$
<i>0711</i>	<i>529 40</i>	92.12 ± 0.56	$5.04^{+0.10}_{-0.11}$	$-52.3^{+4.0}_{-3.8}$	$1.2638^{+0.0064}_{-0.0096}$
0815	531 48	93.80 ± 0.51	$4.50^{+0.08}_{-0.09}$	$-52.8^{+4.0}_{-4.1}$	$1.1007^{+0.0066}_{-0.0074}$
0986	534 89	93.14 ± 0.45	$4.54^{+0.08}_{-0.08}$	$-50.5^{+4.0}_{-4.0}$	$1.0883^{+0.0075}_{-0.0066}$
1060	536 36	92.97 ± 0.47	$4.58^{+0.08}_{-0.08}$	$-49.2^{+3.8}_{-3.9}$	$1.1028^{+0.0064}_{-0.0055}$
1086	536 87	92.24 ± 0.41	$4.61^{+0.07}_{-0.07}$	$-46.2^{+3.8}_{-3.9}$	$1.0860^{+0.0061}_{-0.0080}$
1181	538 77	92.11 ± 0.59	$4.68^{+0.10}_{-0.11}$	$-48.2^{+4.5}_{-4.6}$	$1.1061^{+0.0039}_{-0.0083}$
1265	540 45	92.35 ± 0.58	$4.65^{+0.10}_{-0.10}$	$-46.1^{+4.2}_{-4.7}$	$1.1130^{+0.0080}_{-0.0100}$
1356	542 26	91.35 ± 0.71	$4.76^{+0.13}_{-0.13}$	$-44.4^{+5.3}_{-5.7}$	$1.1110^{+0.0040}_{-0.0120}$
1454	544 21	91.17 ± 0.54	$4.71^{+0.10}_{-0.10}$	$-40.9^{+4.1}_{-4.6}$	$1.0900^{+0.0060}_{-0.0079}$
Observations since Hohle et al. (2009)					
1700	549 12	91.05 ± 0.75	$4.76^{+0.14}_{-0.14}$	$-41.6^{+5.6}_{-5.9}$	$1.1042^{+0.0096}_{-0.0120}$
1792	550 96	90.08 ± 0.96	$4.87^{+0.18}_{-0.18}$	$-39.1^{+7.1}_{-7.3}$	$1.1067^{+0.0110}_{-0.0140}$
2076	556 62	89.69 ± 0.65	$4.80^{+0.12}_{-0.13}$	$-29.1^{+5.2}_{-5.5}$	$1.0841^{+0.0098}_{-0.0120}$
2087	556 84	89.80 ± 0.71	$4.84^{+0.13}_{-0.14}$	$-32.4^{+5.2}_{-5.5}$	$1.0990^{+0.0040}_{-0.0081}$
2163	558 35	89.34 ± 0.54	$4.87^{+0.10}_{-0.11}$	$-35.3^{+4.1}_{-4.5}$	$1.0776^{+0.0063}_{-0.0110}$

Due to the lack of a sufficient amount of photons for the individual spectra, we used the *Chandra* data for timing analysis only.

3 RESULTS

3.1 Spectral behaviour

To investigate the spectral evolution of RX J0720 we first fitted all 16 EPIC-pn spectra obtained in FF mode with a thin filter in one session using XSPEC12. We used the model $phabs*(bbodyrad+gaussian)$, as also used in Haberl et al. (2004, 2006), Haberl (2007), Hohle et al. (2009) and Hohle et al. (2012), where *gaussian* is used to account for the broad absorption feature at 0.3 keV. The simultaneous fit of the 16 EPIC-pn data sets resulted in $\chi^2/d.o.f = 1.23$ with 2374 degrees of freedom. We obtained $N_H = 0.984 \pm 0.050 \times 10^{20} \text{ cm}^{-2}$ for interstellar absorption, $E_{\text{line}} = 311.9 \pm 5.0 \text{ eV}$ for the central energy and $\sigma = 64.4 \pm 3.5 \text{ eV}$ for the line width of the broad absorption feature (all errors denote 90 per cent confidence level). These three parameters were assumed to be constant for all observations, as

in previous works (Haberl et al. 2004, 2006; Haberl 2007; Hohle et al. 2009). The blackbody temperature (kT), emitting radius (R), computed assuming a distance of $D = 300 \text{ pc}$, see Kaplan, van Kerkwijk & Anderson 2007; Eisenbeiss 2011) and the line EW were allowed to vary between the observations.

Due to cross-calibration and pile-up issues for the normalization (see Haberl et al. 2004 for a detailed discussion), the data obtained with other instrument setups (revolution 0175 with a medium filter and revolution 0711 in SW mode and medium filter) were fitted separately, but fixing N_H , E_{line} and σ at the values obtained from the simultaneous fit of the 16 EPIC-pn spectra performed in FF mode with a thin filter, see Table 2 and Fig. 1.

As reported already in Haberl et al. (2006), the temperature, size of the emitting area and EW underwent major changes around MJD = 53000 d, but since then (i.e. over the last seven years), all three parameters changed only gradually. *XMM-Newton* observations cover now a time-span of almost 12 yr; hence, a 7.5 yr period can be excluded. A 14 yr period seems unlikely, since if one extrapolates the spectral evolution (Fig. 1) for two further years,

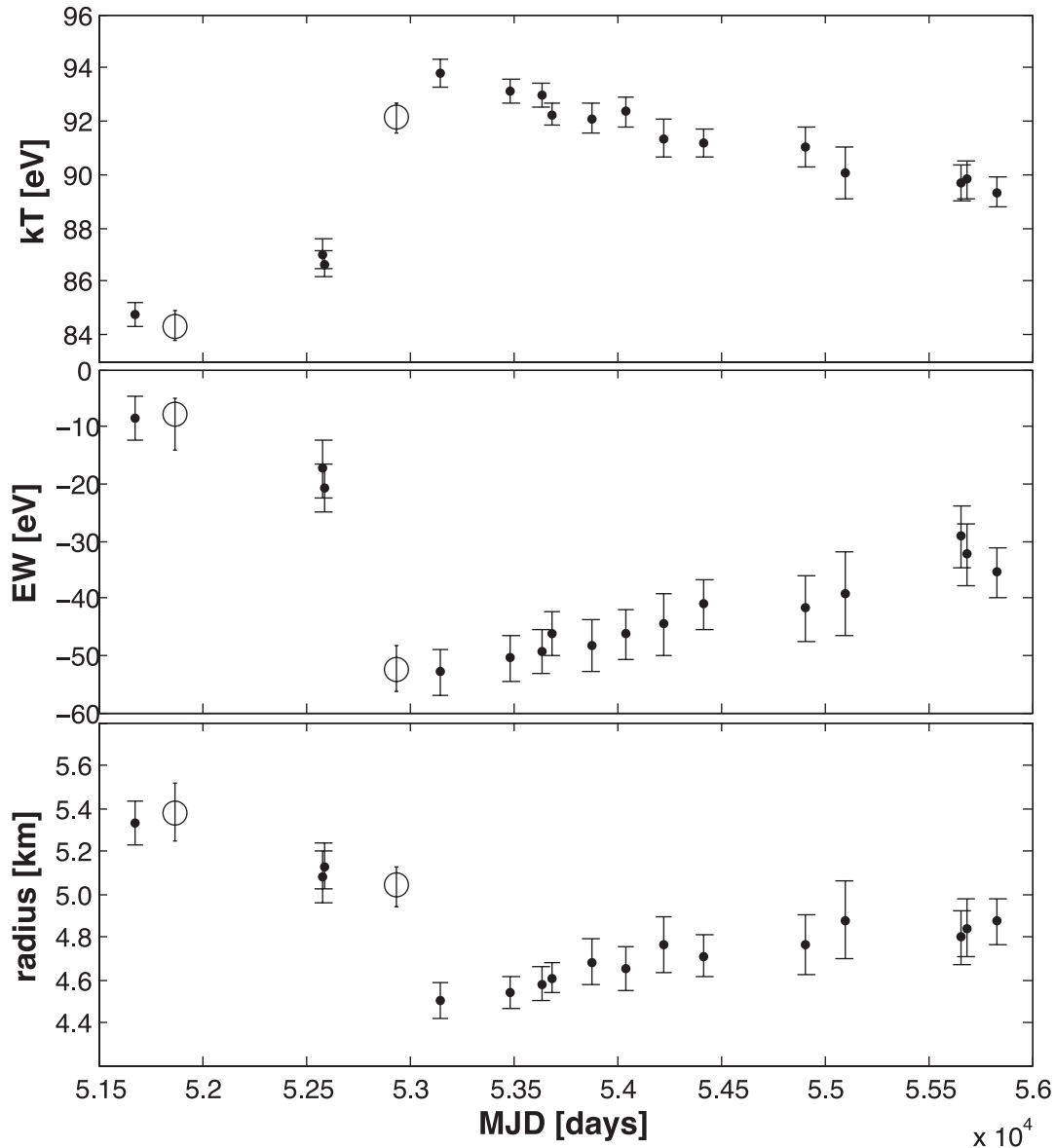


Figure 1. Spectral properties of RX J0720, as listed in Table 2.

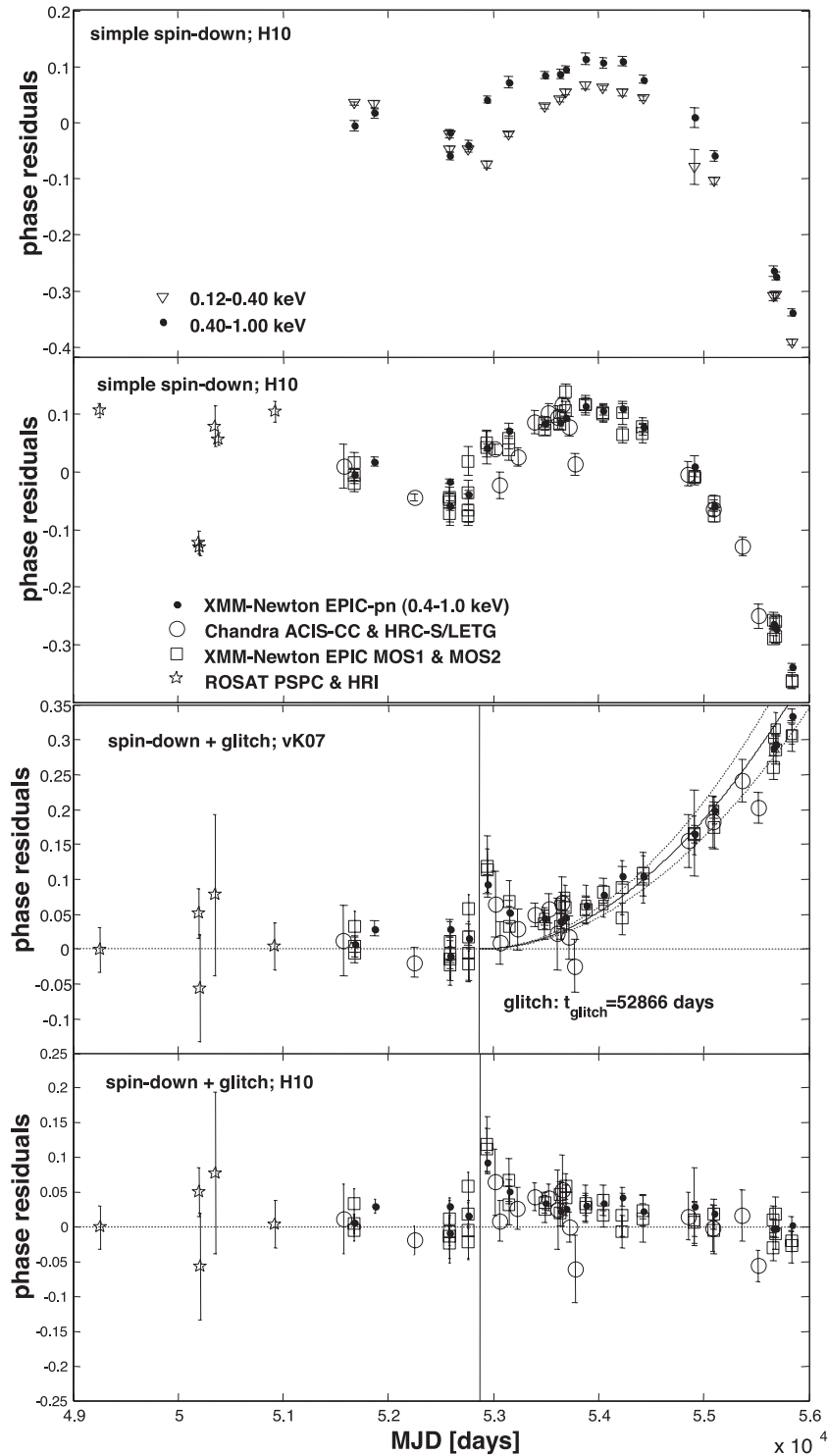


Figure 2. Phase residuals of RX J0720 after applying the phase coherent ‘all data’ timing solution in Hohle et al. (2010, H10) with constant spin-down (upper two panels). The top panel illustrates the variable phase shift between soft (0.12–0.40 keV) and hard (0.40–1.00 keV) photons seen in the EPIC-pn data. The glitch solution proposed by van Kerkwijk et al. (2007, vK07) fits well the data available at this time (MJD = 535 00 d), but poorly represents the data at later epochs (third panel). The later (deviant) points require an additional quadratic term (shown with its 1σ uncertainty) to be explained; this corresponds to a modification of the spin-down parameter \dot{f} for $t > t_g$ (Hohle et al. 2010). The phase residuals from the most recent observations (after MJD = 551 00 d) are consistent with the modified glitch solution (lower panel). The glitch time t_g at MJD = 52866 ± 73 d is indicated by the solid vertical line in the lower two panels. All error bars correspond to 1σ confidence.

the spectral properties are still significantly different to their initial values.

3.2 Timing

Applying the ‘all data’ solution with constant spin-down, Hohle et al. (2010) found that the phase residuals of RX J0720 have shown a long-term behaviour with a possible periodic pattern yielding a 7–9 yr or a 14–16 yr period (depending on assumptions) until summer 2010 (MJD \approx 554 00 d). Therefore, it was expected that the phase residuals (which were negative at the time of the previous investigation) will approach zero for the next observations. However, the phase residuals still reach large and negative values, if the ‘all data’ solution in Hohle et al. (2010) is applied (Fig. 2, upper two panels) to the new data. Also the variable phase shift between soft and hard photons (Fig. 2, upper panel) stays constant since the last observations, whereas it was expected that the phase shift will reverse sign again, as occurred around MJD = 530 00 d, if RX J0720 precesses.

van Kerkwijk et al. (2007) proposed a ‘glitch solution’ to explain the timing behaviour of RX J0720, which fits well the data available at that time (see Fig. 2, third panel), but does not represent the data after MJD = 535 00 d. Hohle et al. (2010) modified the ‘glitch solution’ of van Kerkwijk et al. (2007) by including a change in spin-down \dot{f}_c , valid for $t > t_g$ (Table 3). This term corrects the drift of the phase residuals in Fig. 2 (third panel), since the time-span available for van Kerkwijk et al. (2007) was too short for a more accurate extrapolation of the phase. Including \dot{f}_c , even the phase residuals of the data that were not available to Hohle et al. (2010, i.e. after MJD = 551 00 d) are consistent with zero (Fig. 2, lowest panel). Hence, the ‘glitch solution’ of van Kerkwijk et al. (2007) with the update of Hohle et al. (2010) models the timing behaviour of RX J0720 much better than a timing solution with constant spin-down.

4 DISCUSSION

The present data of RX J0720 do not support a cyclic behaviour with a period in the 7–14 yr range in the spectral and timing properties of the source. However, the measured blackbody temperature is still declining and, by extrapolating the linear trend (since the proposed glitch time $t_g = 528\,66 \pm 73$ d), RX J0720 will reach its initial state in autumn 2019. It is of interest to follow this decline and assessing whether the temperature will finally stabilize at the pre-2003 value. This requires a monitoring for at least 20 yr in total (out of which 11 yr have been already covered) to reveal any long-term periodicity.

Table 3. The timing parameters of the glitch solution (van Kerkwijk et al. 2007) for RX J0720 with \dot{f}_c for $t > t_g$. The numbers in parentheses indicate the 2σ errors. The phase is determined by $\Phi(t) = \Phi(t_0) + f(t - t_0) + 0.5 \cdot \dot{f}(t - t_0)^2 - 0.5 \cdot \dot{f}_c(t - t_0)^2 + \Delta\Phi_g(t)$, with $\Delta\Phi_g(t) = -\Delta f(t - t_0) - 0.5 \cdot \Delta\dot{f}(t - t_0)^2$ and $\Delta\Phi_g(t) = 0$ for $t > t_g$.

t_0 (MJD)	530 10.263 5667(10)
f (Hz)	0.119 173 6716(9)
\dot{f} (10^{-15} Hz s $^{-1}$)	−1.04(3)
t_g (MJD)	528 66(73)
Δf (mHz)	4.1(12)
$\Delta\dot{f}$ (10^{-17} Hz s $^{-1}$)	−4(3)
\dot{f}_c (10^{-17} Hz s $^{-1}$)	−1.11(20)

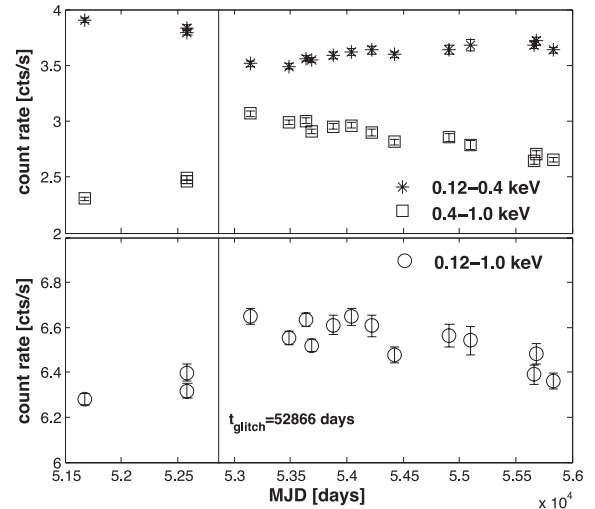


Figure 3. The evolution of the count rates of RX J0720 in the soft and hard band (upper panel), and the total count rate (lower panel). The data are obtained for the observations performed with *XMM-Newton* EPIC-pn in FF mode with a thin filter (errors denote 90 per cent confidence level).

It is not possible to explain both the spectral and temporal changes of RX J0720 by precession with a self-consistent model similar to that discussed in Haberl et al. (2006), fig. 5 therein. This might reflect the lack of knowledge regarding the exact emission geometry (spot shape, temperature distribution, atmospheric effects, etc.) of this NS.

The ‘glitch solution’ of van Kerkwijk et al. (2007) fits well the phase residuals, if the modification by Hohle et al. (2010) is applied. The jump in frequency at MJD = $528\,66 \pm 73$ d would correspond to the gain of angular momentum imparted by a mass of 10^{20} – 10^{21} g accreted by the NS (van Kerkwijk et al. 2007). Hence, the glitch might have been caused by an accretion event e.g. the impact of an asteroid. Recently, some evidence for a disc or a dense ($n_H = 10$ – 10^{10} cm $^{-3}$) ambient medium around RX J0720 was discussed (Hambaryan et al. 2009; Hohle et al. 2012). This (still) hypothetic disc may host material for such an impact (see discussion in Hohle et al. 2012). However, as illustrated in Fig. 1, the spectral changes occurred already before MJD = $528\,66 \pm 73$ d and this would point rather to a slow change than a sudden event. Also, the variable phase lag between soft and hard photons is difficult to reconcile with an impact. Moreover, the total flux (120–1000 eV, Table 2) of RX J0720 remained almost constant, but the fluxes in the soft and the hard band changed significantly (the spectrum became harder until MJD \approx 530 00 d and now it is softening again, see Fig. 3, suggesting the existence of at least two emission regions with different temperatures). The best-fitting blackbody temperature and size of the emitting area show changes of \approx 10–20 per cent. However, it is remarkable that these changes somehow conspire to keep the flux within 10 per cent variation, showing that the changes cannot be caused by a sudden heating alone.

In the case of a glitch or an impact, the total flux is expected to increase. The changes indicate a rearrangement of the flux, rather than heating by a glitch. The long-term changes in the absorption feature are also suggestive of some gradual, non-impulsive mechanism behind the timing behaviour of the source. This leads to the conclusion that the spectral and temporal evolution of RX J0720 might be caused by magnetospheric distortions, and hence a rearrangement of the magnetic field. Note that the broad-band luminosity remains constant in the X-rays, but the source was not monitored at optical

and ultraviolet wavelengths (Motch & Haberl 1998; Kaplan et al. 2003; Motch, Zavlin & Haberl 2003; Eisenbeiss et al. 2010).

RX J0720 is close to magnetars in the $P-\dot{P}$ diagram. In particular, evolutionary connections between the M7 and the soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) have been discussed by many authors (Heyl & Kulkarni 1998; Kaplan & van Kerkwijk 2009b; Popov et al. 2010). AXPs and SGRs have similar pulse periods and are younger (by a factor of 10–100) than the M7. Despite low statistics (only ≈ 10 objects in each group are observed) and the unsettled properties of some objects, Popov et al. (2010) have shown that the different families of NSs can be explained by one evolutionary model. A possibility, then, is that the M7 descend from SGRs/AXPs and are aged magnetars in which the magnetic dipole field decayed from the initial $\approx 10^{14}$ G to the present $\approx 10^{13}$ G. The decay of the surface field is actually triggered by the decay of the internal, toroidal and poloidal one. It is the progressive exhaustion of internal magnetic helicity that is responsible for the low-level activity of old magnetars (bursting/outbursting behaviour and non-thermal X-ray spectral components). The recent discovery of a low-field SGR (Rea et al. 2010) and its likely interpretation as an aged magnetar (Turolla et al. 2011) lends further support to this picture. It could be that, contrary to SGR 0418+5729, the initial internal toroidal field in RX J0720 was not strong enough to power an outburst in its late stages of evolution (Perna & Pons 2011) and the last hiccups of activity were seen as moderate changes in the spectral and timing properties. In this case, we should witness more erratic spectral and temporal irregularities in the future, if the monitoring of RX J0720 will be continued.

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