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The XMM-Newton view of radio-quiet and X-ray dim isolated neutron stars

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Abstract. As part of the guaranteed time, guest observer and calibration programs, *XMM-Newton* extensively observed a group of six thermally emitting, isolated neutron stars which are neither connected with a supernova remnant nor show pulsed radio emission. The high statistical quality of the EPIC data allows a detailed and homogeneous analysis of their temporal and spectral properties.
Four of the six sources are now well established as X-ray pulsars: The 11.37 s period discovered in EPIC-pn data of RX J0806.4−4123 was confirmed in a second *XMM-Newton* observation. In the case of the X-ray faintest of the six stars, RX J0420.0−5022 the period marginally indicated in ROSAT data was not seen in the EPIC data, instead a 3.45 s pulse period was clearly detected. Spectral variations with pulse phase were discovered for the known 8.39 s pulsar RX J0720.4−3125 and also RBS1223. For the latter EPIC data revealed a double-peaked pulse profile for a neutron star spin period of 10.31 s.
The X-ray continuum spectra of all six objects are consistent with a Planckian energy distribution with black-body temperatures kT between 40 eV and 100 eV. EPIC data of the pulsars RBS1223 and RX J0720.4−3125 revealed a broad absorption feature in their spectra at energies of 100-300 eV and ~260 eV, respectively. The depth of this feature varies with pulse phase and may be caused by cyclotron resonance scattering of protons or heavy ions in a strong magnetic field. In such a picture the inferred field strength exceeds 10^{13} Gauss, in the case of RX J0720.4−3125 consistent with the value estimated from its pulse period derivative. A similar absorption feature in the RGS and EPIC spectra of RX J1605.3+3249 was reported recently.

Key words. X-rays: stars – stars: neutron – stars: magnetic fields

1. Introduction

Presently more than half a dozen ROSAT-discovered X-ray dim isolated neutron stars (XDINs, for recent reviews see Treves et al. 2000; Motch 2001; Haberl 2003) are known which share very similar properties. Their X-ray spectra are characterized by soft blackbody-like emission without indication for harder, non-thermal components. These stars apparently show no pulsed radio emission and no association with supernova remnants. Some of them exhibit pulsations in their X-ray flux indicating the neutron star rotation period. Although there is little doubt that the soft X-rays are of thermal origin from the surface of

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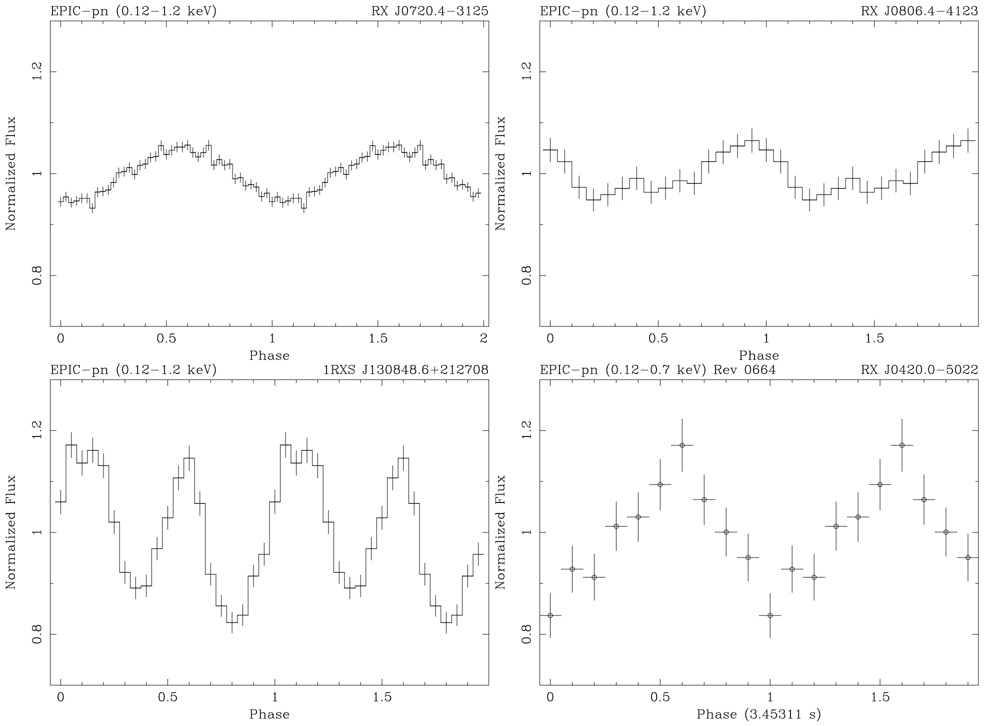

Fig. 1. EPIC-pn light curves folded on the pulse period for the four pulsars among the XDINs.

an isolated neutron star, the details for the formation of the spectrum are not clear. *XMM-Newton* observed six XDINs as part of the guaranteed time, guest observer and calibration programs. Here I summarize some of the first results of a homogeneous analysis of their temporal and spectral properties.

2. X-ray pulsations

The second brightest of the known XDINs is RX J0720.4−3125 and was the first discovered as X-ray pulsar (Haberl et al. 1997) with a period of 8.39 s. *XMM-Newton* observed RX J0720.4−3125 six times. As example the folded EPIC-pn light curve from satellite revolution 534 is drawn in Fig. 1 which shows a pulsed fraction of about 11%. In Chandra data of RBS1223 = 1RXS J130848.6+212708 Hambaryan et al. (2002) discovered pulsations with a period of 5.16 s and *XMM-Newton* observations revealed that the true neutron star spin period is more likely 10.31 s. This is supported by pulse phase dependent hardness ratio variations which are different for the two intensity maxima (Haberl et al. 2003). RBS1223 exhibits the deepest modulation of the known XDINs in its double peaked pulse profile of 18% (Fig. 1). The first *XMM-Newton* observation of RX J0806.4−4123 revealed a 6% modulation (Fig. 1) with a period of 11.37 s (Haberl & Zavlin 2002) which was confirmed in a second observation (Haberl et al. 2004a). Four *XMM-Newton* observations of RX J0420.0−5022 did not confirm the 22.7 s pulsations originally indicated in ROSAT data, but clearly reveal a 3.45 s period. The pulsed fraction is about 12% (Fig. 1). In Table 1 the derived pulse periods for the four pulsars are summarized together with pulse period derivatives assuming linear period changes between multiple *XMM-Newton* observations. In most cases the time base line is too short to determine precise $\dot{P}$ values, only for RX J0720.4−3125 observations by different satellites cover already more than 10 years (Zane et al. 2002; Kaplan et al. 2002).

3. X-ray spectra

The X-ray spectra of XDINs obtained by the ROSAT PSPC were all consistent with black-body emission little attenuated by interstellar absorption suggesting that the objects are close-by. To look for absorption features which may be created by heavy chemical elements in the stellar atmosphere high resolution spectra of RX J1856.4−3754 were obtained by the LETGS on Chandra (Burwitz et al. 2001, 2003). Surprisingly, no significant narrow features were detected.

A spectral analysis (in a homogenous way using the latest calibration data) of the EPIC-pn spectra, which are of unprecedented statistical quality, shows that in several cases a black-body model yields unsatisfactory fits. The strongest deviations are seen from RBS1223 and Haberl et al. (2003) demonstrate that a non-magnetic atmosphere models can neither explain the observed spectrum. However, it was found that adding an absorption feature modeled by a broad (100 eV) Gaussian line at an energy between 100 and 300 eV to the Planckian continuum yields acceptable fits. Similarly, but at a higher energy of 450 eV and therefore inside the sensitive band of the RGS instruments van Kerkwijk (2004) presented the detection of a broad absorption feature in the spectra of RX J1605.3+3249. Haberl et al. (2004b) report a broad absorption feature in the EPIC-pn spectra of the pulsar RX J0720.4−3125 at an energy of 270 eV and find that the depth of the feature varies with pulse phase by a factor of ~2. Finally, also spectra of RX J0420.0−5022 indicate a possible absorption line at 330 eV (Haberl et al. 2004a).

In Table 1 the spectral parameters inferred from the fits using the two models (absorbed black-body and absorbed black-body with Gaussian-shaped absorption line) are listed. The first value given for column density N_H and black-body temperature kT refers to the model without absorption line and the second to the model with line added.

4. Discussion

Four of the six X-ray-dim isolated neutron stars are now known as X-ray pulsars with spin periods between 3.45 s and 11.37 s. The fraction of pulsed flux in their folded X-ray light curves ranges between 6% and 18%. RBS1223, RX J0720.4−3125 and RX J0420.0−5022 show hardness ratio variations with pulse phase (Haberl et al. 2003, 2004b,a) while for RX J0806.4−4123 the shallow modulation makes the significant detection of such an effect more difficult (Haberl et al. 2004a). Pulse phase resolved spectra for the first three pulsars show that the temperature changes only marginally with pulse phase. Any model for the pulsed emission from this group of isolated neutron stars must be able to explain this behaviour.

An important piece of information comes from the detection of broad absorption features in the X-ray spectra of several XDINs. At least in the case of RX J0720.4−3125 the depth of the feature varies strongly with pulse phase. A likely interpretation of these features is cyclotron resonance absorption which can be expected in spectra from magnetized neutron stars with field strength B in the range of 10^{10}–10^{11} G or 2×10^{13}–2×10^{14} G if caused by electrons or protons, respectively. In the case of RX J0720.4−3125 the measured $\dot{P}$, if interpreted as magnetic dipole braking, rules out the lower range for B, leaving protons or highly ionized heavy atoms as origin. The measured line energies, summarized in Table 1, then directly provide a measure for B. The values, assuming proton cyclotron resonance in the magnetosphere of a neutron star with canonical mass and radius are listed in the last column of Table 1. For RX J1856.4−3754 an independent B estimate of about 1.1×10^{13} G can be inferred from the spin-down luminosity required to power the emission nebula (van Kerkwijk & Kulkarni 2001) and the likely age of the star (Trümper et al. 2004). This is similar to the values derived for the other stars but may just be outside the range observable at soft X-rays via cyclotron lines.

Table 1. X-ray-dim isolated neutron stars observed by *XMM-Newton*

Source	P (s)	$\dot{P}$ ($\mathrm{s\,s^{-1}}$)	N_H $10^{20}\ \mathrm{cm^{-2}}$	kT (eV)	E_{line} (eV)	B 10^{13} G
RX J0420.0−5022	3.453	$< 9 \times 10^{-12}$	1.0/2.0	45/45	330?	6?
RX J0720.4−3125	8.391	$(3-6) \times 10^{-14}$	1.4/0.8	85/84	270	5
RX J0806.4−4123	11.371	$< 2 \times 10^{-12}$	0.4	96	–	
RBS1223	10.313	$< 6 \times 10^{-12}$	7.1/4.1	95/86	100-300	2-6
RX J1605.3+3249	–	–	0.3/0.9	96/93	450	9
RX J1856.5−3754	–	–	0.9	60	–	1?

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