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Long term hard X-ray variability of the anomalous X-ray pulsar 1RXS J170849.0–400910 discovered with *INTEGRAL*

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ABSTRACT

Aims. We report on a multi-band high-energy observing campaign aimed at studying the long term spectral variability of the Anomalous X-ray Pulsar (AXP) 1RXS J170849.0−400910, one of the magnetar candidates.
Methods. We observed 1RXS J170849.0−400910 in Fall 2006 and Spring 2007 simultaneously with *Swift*/XRT, in the 0.1–10 keV energy range, and with *INTEGRAL*/IBIS, in the 20–200 keV energy range. Furthermore, we also reanalyzed, using the latest calibration and software, all the publicly available *INTEGRAL* data since 2002, and the soft X-ray data starting from 1999 taken using *BeppoSAX*, *Chandra*, *XMM-Newton* and *Swift*/XRT, in order to study the soft and hard X-ray spectral variability of 1RXS J170849.0−400910.
Results. We find a long-term variability of the hard X-ray flux, extending the hardness-intensity correlation proposed for this source over 2 orders of magnitude in energy.

Key words. gamma-rays: observations – pulsars: individual 1RXS J170849.0−400910 – pulsars: general

1. Introduction

Anomalous X-ray Pulsars (AXPs, Mereghetti et al. 2002) are a peculiar subclass of X-ray pulsars which share the following properties: a narrow range of spin periods (P = 5–12 s), a typical X-ray luminosity of $L_X \sim 10^{34}$–10^{36} erg s^{-1}, no evidence for Doppler shifts in the light curve, the lack of bright optical companions – indicating their isolated nature – and a spin down in the range 10^{-13}–10^{-10} s s^{-1}. Their soft X-ray spectra are generally well described by a two component model, made of a black body with $kT \sim 0.4$–0.5 keV, and a steep power law (see Woods & Thompson 2006, and references therein). The detection of Soft Gamma-ray Repeater-like bursts from five AXPs (e.g. Gavriil et al. 2002) has pushed forward the interpretation of the AXPs as magnetars, i.e. neutron stars with an ultra-high magnetic field (B ∼10^{14-15} G). The magnetar model (Duncan & Thompson 1992), developed initially to describe the SGRs phenomenology (bursts, timing, persistent emission), seems quite capable to describe the AXPs characteristics as well.

Since the AXPs spectra below ∼10 keV are rather soft, the first *INTEGRAL* detections above 20 keV of very hard high-energy tails associated with these objects came as a surprise (Kuiper et al. 2006; den Hartog et al. 2006; Revnivtsev et al. 2004; Mereghetti et al. 2005; Molkov et al. 2005; Götz et al. 2006). AXP spectra flatten (Γ ∼ 1) above 20 keV and the pulsed fraction of some of them reaches up to 100% (Kuiper et al. 2006). The discovery of these hard tails provides new constraints on the emission models for these objects since their luminosities might well be dominated by hard, rather than soft, X-rays.

1RXS J170849.0−400910 was discovered during the *ROSAT* all sky survey. The measure of its period (Sugizaki et al. 1997), period derivative (Kaspi & Gavriil 2003) and general X-ray properties (Israel et al. 1999), made it an AXP member. Interesting results have been reported by Rea et al. (2005), who claimed a correlation between the soft X-ray flux and spectral hardness, with a marginal evidence of the highest and hardest spectra being correlated with the AXP glitching activity (Dall'Osso et al. 2003; Kaspi et al. 2000; Israel et al. 2007). This correlation has been recently confirmed by Campana et al. (2007), Rea et al. (2007a), and Israel et al. (2007) using further *Chandra*, *Swift*/XRT and *RXTE* data, but always focussing on a limited energy interval (i.e. below ∼10 keV).

In this paper, we present our recent multi-wavelength observation campaign carried out with *INTEGRAL* (Winkler et al. 2003) and *Swift* (Gehrels et al. 2004). These new data, together with a re-analysis of all publicly available *INTEGRAL*, and soft X-ray observations of 1RXS J170849.0−400910, allow us to investigate the timing and spectral properties of the source over a broader energy range. For our timing analysis we made use of the solution recently derived by Israel et al. (2007), see Table 3. We report a long-term correlation between the soft and hard X-ray emission. Results are discussed in the framework of the magnetar model.

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2. Observations and Data Reduction

2.1. *INTEGRAL/IBIS observations*

We selected and analyzed all publicly available IBIS (*INTEGRAL* coded mask imager; Ubertini et al. 2003) pointings within 12° from the direction of the source, for a total of 2550 pointings of 2–3 ks each. In addition, we analyzed our data of the Key Programme observation of the Galactic Centre, 622 pointings performed in Fall 2006, and Spring 2007, since, thanks to its large field of view (29°×29°), the source was almost always covered during these observations. Our analysis is based on data taken with ISGRI (Lebrun et al. 2003), the IBIS low energy detector array, which is made of CdTe crystals, and is working in the 15 keV–1 MeV energy range.

We processed the data using the Offline Scientific Analysis (OSA) software provided by the *INTEGRAL* Science Data Centre (ISDC, Courvoisier et al. 2003) v6.0. We produced the images of each pointing in ten energy bands between 20 and 300 keV. We then added up the images in order to detect the source in the 20–70 keV energy range. To investigate the broad-band temporal X-ray variability, the observations were ganged-up to overlap available soft X-ray data sets. The six data segments used in this study are shown in Table 1. From each of these segments we derived spectra from the mosaicked images in the 10 energy bands.

Table 1. *INTEGRAL* observations and results. Errors are at 1 σ c.l.

Obs. Number	T_{Start} MJD	T_{Stop} MJD	Exposure Ms	Type[a]	20–70 keV Flux[b]
1	52698.32	52751.59	0.83	P	0.41±0.06
2	52859.63	52919.88	1.16	P	0.27±0.06
3	53226.18	53298.48	1.0	P	0.42±0.06
4	53408.32	53481.27	1.5	P	0.44±0.05
5	53990.59	54013.77	0.46	KP	0.16±0.09
6	54159.36	54184.07	0.52	KP	0.23±0.09

[a] P = Public ; KP = Key Programme.
[b] In units of counts s^{-1} on the ISGRI camera.

2.2. *X-ray observations*

We re-analysed all the public available recent data of 1RXS J170849.0−400910 taken with X-ray imaging telescopes in the soft X-rays (i.e. below ∼10 keV). The observation times and exposures for each data set are reported in Table 2.

BeppoSAX, *XMM-Newton* (PN), and *Chandra* data were reduced following the procedures described in Israel et al. (2001); Rea et al. (2003, 2005); Campana et al. (2007), but using the latest available software and calibration files.

For the *Swift*/XRT we analysed only data taken in photon counting (PC) mode. These were reduced using the FTOOLS v6.2 package and CALDB calibration files v20070531 provided by the High Energy Astrophysics Science Archive Research Center. Standard cleaning and selections were applied and spectra were extracted using regions of 40″ and 80″ radius for source and background, respectively. Standard response files have been used (we used v.9 response matrices).

We notice that *BeppoSAX* observed the source also in the 15–300 keV band, with the PDS instrument (Frontera et al. 1997). This non-imaging spectrometer had a field of view of 1.3° (FWHM) and the background subtraction was done with a rocking system, which switched between the source and two offset background regions. The presence of bright contaminating sources in both the background pointings prevented us from analyzing the background subtracted spectra, so we concentrated on the timing analysis of these data and extracted barycentered events files for the on-source position (see Sect. 3.2).

Table 2. X-ray data observations and results. Errors are at 1 σ c.l.

Instrument Name	OBS date MJD	Exposure ks	1–10 KeV Flux[a]	Photon Index
SAX LECS/MECS	51268	26/52	$4.40^{+0.03}_{-0.03}$	$2.63^{+0.07}_{-0.07}$
SAX LECS/MECS	52138	77/199	$4.45^{+0.01}_{-0.02}$	$2.38^{+0.03}_{-0.04}$
Chandra HETG	52526	32	$3.9^{+0.1}_{-0.2}$	$2.39^{+0.12}_{-0.12}$
XMM-Newton PN	52879	31	$3.00^{+0.01}_{-0.01}$	$2.77^{+0.01}_{-0.01}$
Chandra CC	53189	29	$3.82^{+0.08}_{-0.10}$	$2.74^{+0.04}_{-0.08}$
Swift XRT	53425	12	$4.28^{+0.11}_{-0.08}$	$2.47^{+0.06}_{-0.06}$
Swift XRT	54017	9	$2.88^{+0.09}_{-0.09}$	$2.99^{+0.05}_{-0.05}$
Swift XRT	54182	4	$3.26^{+0.12}_{-0.13}$	$2.76^{+0.08}_{-0.06}$

[a] Absorbed flux in units of 10^{-11} erg cm^{-2} s^{-1}.

3. Analysis and Results

3.1. *Spectral analysis*

The spectral parameters reported in Table 2 have been derived by fitting all the datasets simultaneously in 1–10 keV energy range (except for *Chandra* data which were limited to 8 keV) by using an absorbed black body plus power law model, with a multiplicative constant factor taking into account inter-calibration issues, not allowed to vary for the same instrument and observing mode. While the parameters of the power law have been left free to vary, the absorption column density, and the black body temperature have been forced to be the same for all instruments. We found a good fit (χ^2/d.o.f. = 1188/1264 = 0.94), and the derived values were $N_H = 1.36(1) \times 10^{22}$ cm^{-2} (solar abundances assumed from Anders & Grevesse 1989, and photoelectric cross-section from Balucinska-Church & McCammon 1992), and $kT = 0.44(1)$ keV; we verified that, if leaving these parameters free to vary, they do not change significantly among all the observations. The fluxes and photon indices are reported in Table 2 and Fig. 1[1]. Our new XRT observation campaign (last two points in Fig. 1) shows that the source entered a new low/soft state (similar to the one measured with *XMM-Newton* in 2003), with a flux a factor ∼1.5 lower than the one measured with XRT in 2005. By adding these new points to the long term variability study of the source, we confirm the flux-hardness correlation proposed by Rea et al. (2005). We also notice that the last three points reported in Fig. 1 are particularly compelling since, being taken with the same instrument (*Swift*/XRT), they are not affected by cross-calibration uncertainties. In addition, our new hard-X data show that the long term variation in flux is correlated over more than two orders of magnitude in energy. In fact, IBIS observations taken quasi-simultaneously with the last two XRT ones (i.e. in late 2006 and early 2007) indicate that the source is hardly detected above 20 keV, while the hard X-ray count rates measured before followed well the variations measured in the soft X-ray range (see Table 1 and Fig. 1). Unfortunately, due to the faintness of the source we could not statistically prove spectral changes at high energies, by comparing different *INTEGRAL*

[1] Note that all the spectral values we report here using the latest calibrations and software are consistent with previous findings, except for the XMM flux which, using SAS v. 7.1.0, appears slightly higher than using SAS 5.4.1 as in Rea et al. (2005); the spectral parameters are instead consistent.

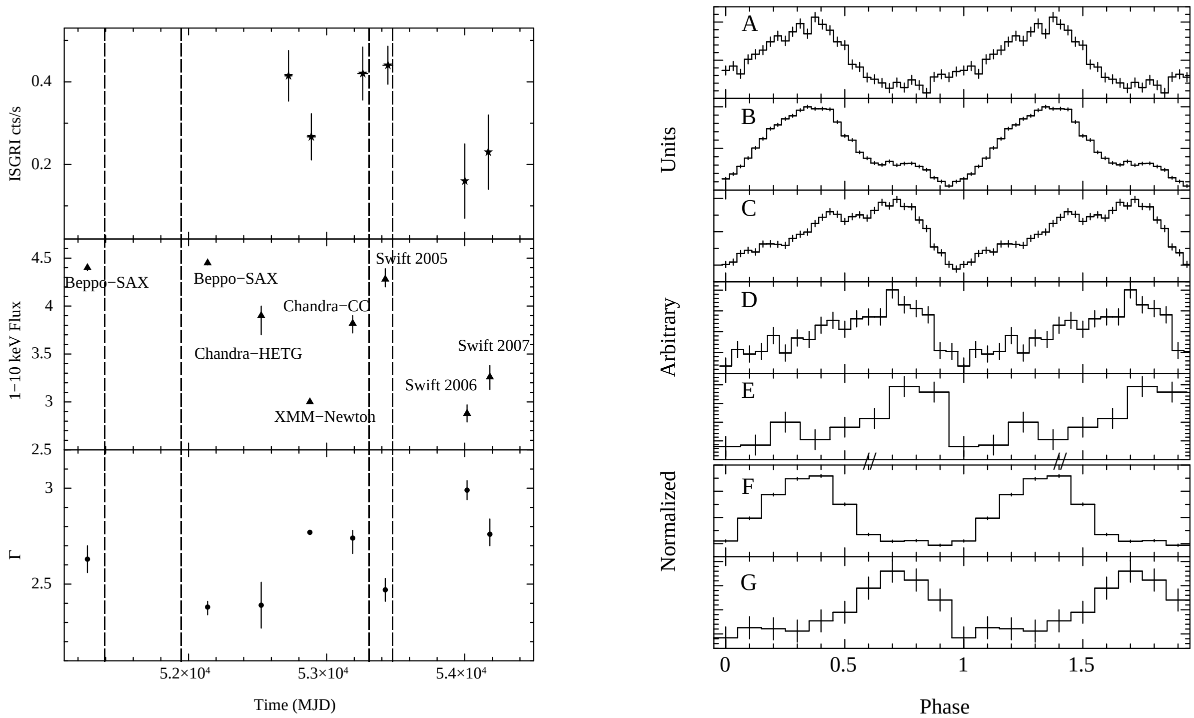

Fig. 1. *Left plot*. Upper Panel: hard X-ray fluxes derived with *INTEGRAL*/IBIS (20–70 keV). Middle Panel: absorbed 1–10 keV fluxes in units of 10^{-11} erg cm^{-2} s^{-1} derived from recent observations of X-ray imaging telescopes as a function of time. Lower Panel: photon indices measured in the 1–10 keV energy band. Vertical dashed lines mark the times of four observed glitches, (see Israel et al. 2007, and references therein). *Right plot*. Folded light curves of 1RXS J170849.0−400910, obtained with *RXTE*/PCA (panels A–D; using the whole 2004 available data) and IBIS data (obs. 3) folded on the *RXTE* timing solution (panel E, data from obs. 3). The energy bands are, from top to bottom: 2.5–4, 4–8, 8–16, 16–32, 20–200 keV. Panels F and G represent the MECS (1–10 keV) and PDS (20–200 keV) light curves registered during the second (2001) *BeppoSAX* observation. Note that panels F and G are phase-aligned between themselves, but not with the others. Errors are for both plots reported at 1 σ c.l.

observations. In order to obtain a statistically significant high energy spectrum, we co-added the IBIS data from observations 3 and 4. The resulting 20–200 keV spectrum is well fitted by a single power law, without the need for a cutoff, with photon index $\Gamma = 1.46 \pm 0.21$. The 20–100 keV flux is $(3.6 \pm 0.5) \times 10^{-11}$ ergs cm^{-2} s^{-1}.

In the attempt to characterize the source spectrum in the low and high state of the source, we fitted simultaneously the IBIS observation 2 with the *XMM-Newton*/PN data and the IBIS observation 4 with the XRT data. We found that the high energy component is well above the extrapolation of the power law derived from soft X-ray data (below ~10 keV), while a three model component, with an additional power-law describing the high energy data points, fits well the entire broadband spectrum (1–200 keV). Motivated by this, we tested if the spectral variations at low energies could be induced just by the variation of the high energy power law. Indeed, by fixing the spectral parameters derived from the *XMM-Newton* observations, one can fit the broad band *XMM/INTEGRAL* (2003) and *Swift/INTEGRAL* observations (2005) by simply changing the slope and normalisation of the high energy power law. Unfortunately, due to the uncertainties in the inter-calibration, and to the low statistic of the *Swift* data, we cannot draw a firm conclusion on this point.

We also modeled the multi-band spectrum in the "low" (2003) and "high" (2005) state with a resonant cyclotron scattering model plus a power-law, and we find a good fit in the "low" state with $\beta = 0.49(1)$, $kT = 0.36(3)$, $\tau = 1.2(1)$ and $\Gamma = 1.0(1)$ (see Rea et al. 2007b for details on the model). In the "high" state, β and kT do not vary, while we found a $\tau = 1.8(1)$ and $\Gamma = 0.8(1)$, which reflects the hardening of the spectrum. The "high" state best fit spectrum is shown in Fig. 2.

3.2. Timing analysis

IBIS data alone do not allow a blind search for timing signatures. In order to perform a timing analysis in the hard X-ray range, we first derived a phase coherent timing solution using publicly available *RXTE*/PCA data covering the same period of the IBIS data. We discovered two new glitches, close to the epoch of our IBIS observations 3 and 4, which are described in detail in Israel et al. (2007). We used the temporal solutions derived there (see Table 3), for the time periods covering the *INTEGRAL* data before and after the first new glitch (and prior the second one). We then extracted the IBIS events in the 20–200 keV band from the pixels that were illuminated by the source for at least the 60% of their surface. To optimize the signal to noise ratio, we restricted our search to the high state periods, namely fall 2004 and spring 2005 (obs. 3 and 4). For

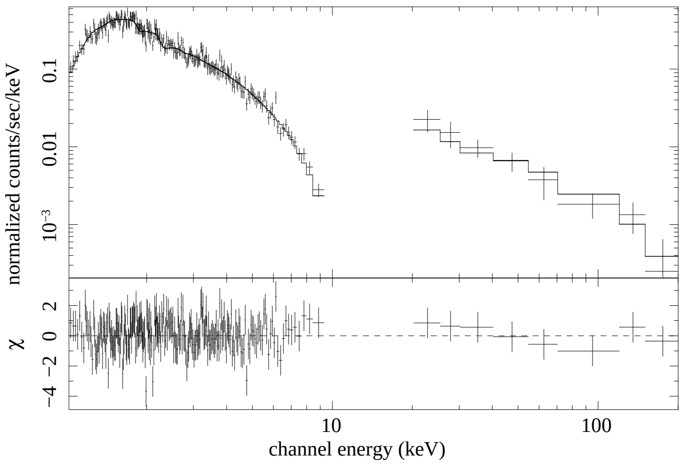

Fig. 2. 2005 “high” state phase averaged spectrum of 1RXS J170849.0−400910. Upper panel: the points below 10 keV are taken with *Swift*/XRT, while above 20 keV IBIS/ISGRI data points are shown. The continuous line represents the best fit model (RCS + power law) described in the text. Lower panel: residuals with respect to the best fit model, plotted as a dashed line.

obs. 3 (obs. 4 results are not reported, but are consistent) we folded the data and, by using the Z^2 test we find that the signal is pulsed at a ~5.7 σ level (chance probability of 1.6×10^{-8}). If we divide the data in two energy bands, 20–60 and 60–200 keV, the significance lowers to 3.2 and 4.2 σ, respectively. The pulse profile of the source, as a function of energy, is shown in Fig. 1. As it can be seen, there is a clear energy dependence of the pulse shape morphology: the peak which is predominant in the soft band disappears and a secondary peak grows with energy becoming the most prominent one above ~8 keV. The pulsed fraction cannot be easily derived from the PCA (a non-imaging instrument) data due to the uncertainties in the background estimation. Besides, the IBIS data are not easy to handle, because of large background variations due the to fact that the source is at different off-axis angles during the different pointings. In addition, due to the large IBIS field of view, the events can be polluted by nearby variable sources. Nevertheless, by averaging the background over the entire IBIS observations, we could measure a pulsed fraction by dividing the difference between the maximum and the minimum of the folded light curves by the count rates derived from imaging. The resulting values are: ~25% (in the 20–60 keV band), ~60% (60–200 keV), and ~40% (20–200 keV).

We did not find significant differences in the IBIS data as far as it concerns the pulsed profiles or the pulsed fraction between observations 3 and 4, i.e. before and after the third glitch reported in Fig. 1

Table 3. Timing solutions used for obs. 3 and 4, derived in Israel et al. (2007)

Obs. Number	Epoch MJD	Period s	Period derivative 10^{-11} s s^{-1}
3	53189.0	11.0023066(2)	1.915(5)
4	53189.0	11.002279(2)	2.01(1)

We also reanalyzed the archival PDS data taken with *BeppoSAX* during the pointings listed in Table 2. Using the timing solutions derived from the simultaneous MECS data (Rea et al. 2003; Israel et al. 2001) we find, and report for the first time, pulsations in the PDS data, in the 20–200 keV energy band. Using Z^2 statistics we did not detect the pulsations in the first dataset, the shorter one, with high confidence (2.7 σ), while in the second dataset they were detected at 5.9 σ. By computing the counts in excess of the phase minimum, we found a 20–200 keV pulsed flux of 0.025 ± 0.010 (for the second observation; the results for the first one are compatible but less significant). By assuming a power-law model with photon index $\Gamma = 1$ for the pulsed spectrum (Kuiper et al. 2006), this gives a flux of ~ 0.7×10^{-11} erg cm^{-2} s^{-1}, slightly lower but still compatible with that derived from IBIS data by using the same approach, namely ~ 10^{-11} erg cm^{-2} s^{-1}.

4. Discussion and Conclusions

We have analyzed all the currently available high energy data (1–200 keV) of 1RXS J170849.0−400910 and continued the long term variability study of the source in the soft X-ray range (≲10 keV), confirming the flux-hardness correlation proposed by Rea et al. (2005) and Campana et al. (2007). Moreover, we report for the first time the discovery of hard X-ray long term flux changes, and show that there is a possible correlation with the flux variations detected at lower energies. Thanks to the dense monitoring of the last years, we are able to correlate these variations with the presence of the two new glitches (discussed in Israel et al. 2007). The only other magnetar for which long term variability in this band has been reported is SGR 1806–20, for which the spectral hardening appears to be correlated with a burst rate increase (Götz et al. 2007).

As proposed in Thompson et al. (2002), Rea et al. (2005), and Campana et al. (2007), an increase in the source activity (bursts, glitches) and a simultaneous spectral hardening may be caused by a growing twist in the magnetosphere; this may be also responsible for the transient appearance of a cyclotron line during the “high” emission state (Rea et al. 2003, 2005). If this is the case, data presented here support models in which also the hard X-ray tails are produced by mechanisms whose strength increases with the twist. Indeed, it may also be that the flux variations in the hard X-rays dominate and drive those detected at lower energies, if the hard X-ray component does not sharply cut off below ~10 keV (as it may be the case for a synchrotron component). Quite recently, Thompson & Beloborodov (2005) discussed how soft gamma-rays may be produced in a twisted magnetosphere, proposing two different scenarios: either thermal bremsstrahlung emission from the surface region heated by returning currents, or synchrotron emission from pairs created higher up (~100 km) in the magnetosphere. While both scenarios predict a power-law-like spectral distribution for the 20-100 keV photons, the cut-offs of the high energy emission are markedly different in the two cases, 100 keV vs. 1 MeV. A third scenario involving resonant magnetic Compton up-scattering of soft X-ray photons by a non-thermal population of highly relativistic electrons has been proposed by Baring & Harding (2007). In this contest we notice that, as for 4U 0142+614 (Rea et al. 2007b), another member of the AXP class, multi-band spectral observations seems to disfavor the thermal bremsstrahlung model. In fact, for any choice of temperature, a model which fits well the data below ~150 keV, will over-predict by more than a factor of 5 the COMPTEL upper limits derived in the MeV band (Kuiper et al. 2006). However, these observations are not simultaneous and due to the variability of the source, no firm conclusion can be drawn.

IBIS data confirm the large pulsed fraction 25%–60%, growing with energy, which has been reported earlier at high energies for other AXPs (and for 1RXS J170849.0−400910 using a different data set) by Kuiper et al. (2006). There is a clear indication for a phase difference of $\Delta\phi \sim 0.3 - 0.4$ between the maxima of the soft (<8 keV) and hard (>8 keV) X-rays light curves measured in the 2004 with ISGRI/PCA data (see Fig. 1). The same phase shift was already present in the 2001 MECS/PDS data: within the errors, we find no evidence for any significant evolution in $\Delta\phi$ or pulsed flux, despite the three glitches that occurred between the observations. The phase shift, similar to the one detected at lower energies (Rea et al. 2003), still lacks a clear interpretation in the magnetar framework, and it may indicate that the location of production of the two (soft/hard) component is different, but stable with time.

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