

XMM-NEWTON DISCOVERY OF 7 s PULSATIONS IN THE ISOLATED NEUTRON STAR RX J1856.5–3754

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ABSTRACT

Thanks to the high counting statistics provided by a recent *XMM-Newton* observation of RX J1856.5–3754, we have discovered that this isolated neutron star pulsates at a period of 7.055 s. This confirms that RX J1856.5–3754 is similar in nature to the other six thermally emitting, nearby neutron stars discovered in soft X-rays with *ROSAT*. The pulsations are detected at consistent periods in several *XMM-Newton* observations spanning from 2002 April to 2006 October, yielding an upper limit of $\dot{P} < 1.9 \times 10^{-12} \text{ s s}^{-1}$ (90% c.l.) on the period derivative. This implies a surface magnetic field smaller than $1.2 \times 10^{14} \text{ G}$, under the usual assumption of vacuum dipole magnetic braking. The pulse profile is nearly sinusoidal with a pulsed fraction in the 0.15–1.2 keV range of only $\sim 1.2\%$, the smallest ever seen in an isolated X-ray pulsar.

Subject headings: pulsars: general — stars: individual (RX J1856.5–3754) — stars: neutron

1. INTRODUCTION

The soft X-ray source RX J1856.5–3754 belongs to a small group of seven nearby, isolated neutron stars discovered with the *Röntgensatellit* (*ROSAT*) and often dubbed X-ray–dim isolated neutron stars (XDINSs; see Haberl 2006 for a recent review). These sources are characterized by thermal spectra with blackbody temperature in the range 40–110 eV, X-ray luminosity of 10^{30} – $10^{32} \text{ ergs s}^{-1}$, faint optical counterparts ($V > 25$), and absence of radio emission. The initial suggestion that XDINSs could be powered by accretion from the interstellar medium (Walter et al. 1996) has been ruled out by the measurement, in three of them, of large proper motions that imply an accretion rate far too small to power the observed luminosity (see, e.g., Motch et al. 2005 and references therein). Pulsations have been found in five (or possibly six) XDINSs, with periods in the 3–12 s range, pulsed fractions between 4% and 18%, and, in two cases, period derivatives of the order of $10^{-13} \text{ s s}^{-1}$ (Kaplan & van Kerkwijk 2005a, 2005b). These spin-down values yield characteristic ages of ~ 1 –2 Myr, spin-down luminosities of $(4\text{--}5) \times 10^{30} \text{ ergs s}^{-1}$, and, with the canonical dipole radiation braking assumptions, magnetic fields of a few times 10^{13} G . It is thus believed that the X-ray emission in XDINSs is powered by the neutron star cooling.

RX J1856.5–3754 received particular interest since it is the brightest XDIN, its X-ray flux does not show any apparent contamination from non thermal magnetospheric emission, and a parallax distance ($117 \pm 12 \text{ pc}$) has been reported (Walter & Lattimer 2002). These properties make RX J1856.5–3754 an ideal target to derive information on the neutron star radius and thus constrain the equation of state of matter at super nuclear density through a detailed modeling of its surface thermal emission. Quite surprisingly, even the X-ray spectra with the highest resolution and the best statistics, obtained in long *Chandra* and *XMM-Newton* observations, do not show any line feature and can be fit by a simple Planckian with temperature $kT = 63 \text{ eV}$ (Burwitz et al. 2003).

Despite extensive searches, no pulsations have ever been detected in RX J1856.5–3754 (Pons et al. 2002; Ransom et al. 2002; Drake et al. 2002; Burwitz et al. 2003). The tight upper limits on the pulsed fraction ($< 1.3\%$ at 2σ) obtained for periods between 0.02 and 1000 s (Burwitz et al. 2003) led to the speculation that RX J1856.5–3754 could be a millisecond pulsar, not yet seen to pulsate owing to the reduced sensitivity for short periods of the observations carried out up to now. Recently, an

upper limit on the pulsed fraction of 2.1% (at 1σ) was reported for periods in the range 1–20 ms (Zavlin 2006). Here we report the discovery of pulsations at 7 s, obtained thanks to the very high counting statistics provided by the most recent *XMM-Newton* observation of RX J1856.5–3754.

2. TIMING ANALYSIS AND RESULTS

A 70 ks long observation of RX J1856.5–3754 was carried out with the *XMM-Newton* satellite starting on 2006 October 24 at 00:30 UT. We used the data of the EPIC instrument (0.1–12 keV), consisting of two MOS cameras and one pn camera (Turner et al. 2001; Strüder et al. 2001). All the cameras mounted the thin filter and were operated in Small Window mode, yielding time resolutions of 6 ms and 0.3 s for the pn and MOS, respectively. We processed the data using version 7.0 of the *XMM-Newton* Science Analysis System; the event files were created using the tasks `epproc` and `emproc` with default options and filtered to exclude the time intervals of high particle background, resulting in net (dead-time–corrected) exposure times of 47 and 68 ks for the pn and MOS, respectively.

We started the timing analysis using the data of the pn camera and selecting the energy range 0.15–1.2 keV. Due to the very soft spectrum of RX J1856.5–3754, practically no source photons are detected at higher energies. We used a circular extraction region centered at the source position and with radius $40''$. This resulted in $\sim 356,600$ counts, of which ~ 2700 can be ascribed to the background. The arrival times were corrected to the solar system barycenter. In order to search for periods of a few seconds, as seen in the other sources of this class, we rebinned the counts at $\sim 0.278 \text{ s}$ and computed the Fourier power spectrum. A significant peak in the power spectrum was found at the frequency of 0.14174 Hz. Taking into account the number of searched periods (131,072), the peak value of 38.46 corresponds to a chance probability of 6×10^{-4} . To better estimate the period, we used the epoch folding technique and fitted the peak in the χ^2 versus trial period distribution as described in Leahy (1987) obtaining $P = 7.05514 \pm 0.00007 \text{ s}$. The corresponding folded light curve is shown in the top panel of Figure 1. No significant differences in the pulse profiles were found by dividing the counts in soft and hard energy intervals. The phase-averaged spectrum is well fit with absorbed blackbody parameters fully consistent with those of the previous *XMM-Newton* observations of RX J1856.5–3754

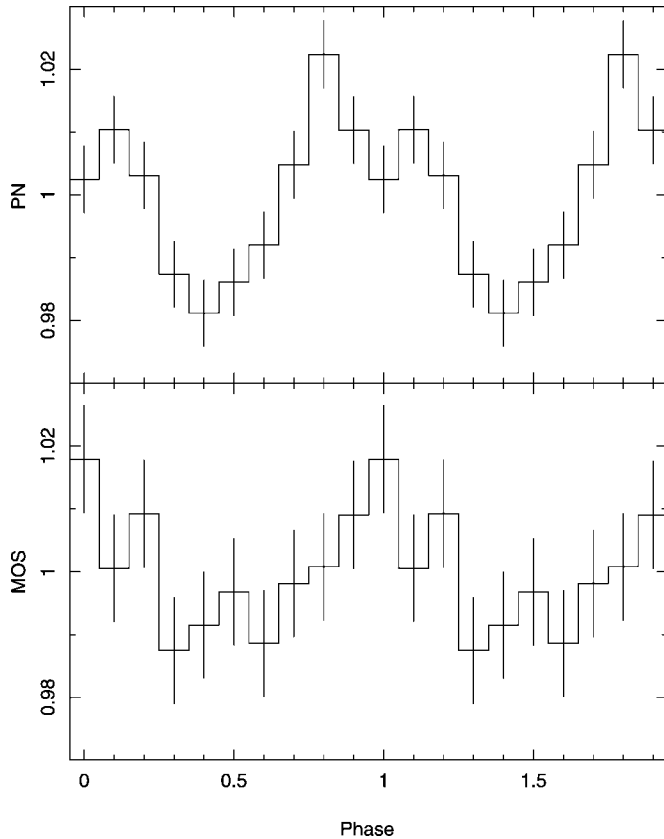


FIG. 1.—Folded light curves of RX J1856.5–3754 in the 0.15–1.2 keV energy range obtained in the 2006 October *XMM-Newton* observation. *Top*: EPIC pn. *Bottom*: EPIC MOS1+MOS2. Fitting the light curves with a constant value gives χ^2 -values of 56.8 (pn) and 8.6 (MOS1+MOS2) for 9 degrees of freedom, corresponding to chance probabilities of 6×10^{-9} and 0.47, respectively.

(Haberl 2006). The pulsed fraction, derived by fitting a sinusoid to the background subtracted pn light curve, is $1.6\% \pm 0.2\%$. This small pulsed fraction explains why the periodicity was not discovered in previous observations and is not significantly detected in the MOS data. The two MOS together collected only $\sim 137,900$ counts from a $40''$ radius extraction region, less

than half of the pn ones. It is thus not surprising that the MOS 0.15–1.2 keV folded light curve (Fig. 1, *bottom*) is statistically consistent with a constant flux.

In order to confirm the periodicity seen in the pn data of 2006 October, we analyzed the other *XMM-Newton* observations listed in Table 1. After reducing the data as described above, we searched for the 7 s pulsations with the Z^2 -test (Buccheri et al. 1983), which has a good sensitivity for sinusoidal signals. For each observation, we restricted our search to the range of periods obtained by a backward extrapolation from the current value, assuming a conservative period derivative $|\dot{P}| < 5 \times 10^{-10} \text{ s s}^{-1}$. During the 2004 April observation the pn was in timing mode and the two MOS were in full-frame mode with a time resolution of only 2.6 s, that caused significant photon pileup in the MOS data. Therefore, we used only the pn data, selecting the energy range 0.28–1.2 keV in order to avoid the soft flares produced by high-energy particles in the pn timing mode (Burwitz et al. 2004). In all the other observations we used the sum of the 0.15–1.2 keV counts from the pn and the two MOS.¹

The distributions that we obtained for the Z^2 -statistics are shown in Figure 2, where it can be seen that a maximum of Z^2 is always present at the expected pulse period. To evaluate the statistical significance of these detections, we must take into account the number of periods searched in each observation. The most significant detection is that of 2002 April, where, considering the 335 independent periods in the considered range (6.98–7.13 s), the peak $Z^2 = 32.22$ corresponds to a chance probability of $335e^{-32.22/2} = 3 \times 10^{-5}$. In a similar way we derived the following chance probabilities for the other observations: 7×10^{-5} (2004 April), 5×10^{-4} (2004 September), 2×10^{-3} (2005 September), and 2×10^{-2} (2006 March).

These values indicate that the periodicity is detected in all the observations, although sometimes with small Z^2 -values, as expected for the case of a small pulsed fraction. The relatively low significance of the 2006 March detection, despite a number of counts and duration similar to the 2006 October observation,

¹ For the 2002 observation the counts below 0.18 keV in the MOS1 were excluded in order to eliminate the electronic noise present in the MOS timing mode.

TABLE 1
LOG OF *XMM-NEWTON* OBSERVATIONS OF RX J1856.5–3754

Date	Instrument	Mode	Exposure (ks)	Counts	Period (s)	Pulsed Fractions (%)
2002 Apr 4–8	pn	SW	40	304,052	7.05510 ± 0.00013	1.4 ± 0.2
	MOS1	TI	57	53,529	...	1.1 ± 0.5
	MOS2	SW	56	82,837	...	0.8 ± 0.4
2004 Apr 4–17	pn	TI	31	109,232	7.05502 ± 0.00012	2.4 ± 0.3
2004 Sep 9–24	pn	SW	23	178,718	7.05524 ± 0.00010	1.1 ± 0.2
	MOS1	SW	68	46,284	...	2.0 ± 0.5
	MOS2	SW	68	52,865	...	2.0 ± 0.5
2005 Sep 9–24	pn	SW	23	169,803	7.05518 ± 0.00027	1.6 ± 0.2
	MOS1	SW	27	26,936	...	0.8 ± 0.6
	MOS2	SW	27	29,706	...	1.5 ± 0.6
2006 Mar 03–26	pn	SW	49	365,050	7.05526 ± 0.00016	0.8 ± 0.2
	MOS1	SW	67	64,895	...	1.4 ± 0.4
	MOS2	SW	67	74,821	...	0.7 ± 0.4
2006 Oct 10–24	pn	SW	47	356,605	7.05514 ± 0.00007	1.6 ± 0.2
	MOS1	SW	68	65,941	...	1.1 ± 0.4
	MOS2	SW	68	71,973	...	1.1 ± 0.4

NOTE.—The exposure times take into account the filtering for high background time intervals and the instrumental dead time. The time resolution of the small window (SW) mode is 6 ms for the pn and 0.3 s for the MOS, while for the Timing (TI) mode it is 0.03 ms for pn and 1.5 ms for MOS. The period values are obtained with the sum of pn and MOS counts. The pulsed fractions are computed from sinusoidal fits of the background-subtracted pulse profiles $[PF = A/C]$, where the count rate is given by $C + A \sin(\phi - \phi_0)$. Errors are at 1σ .

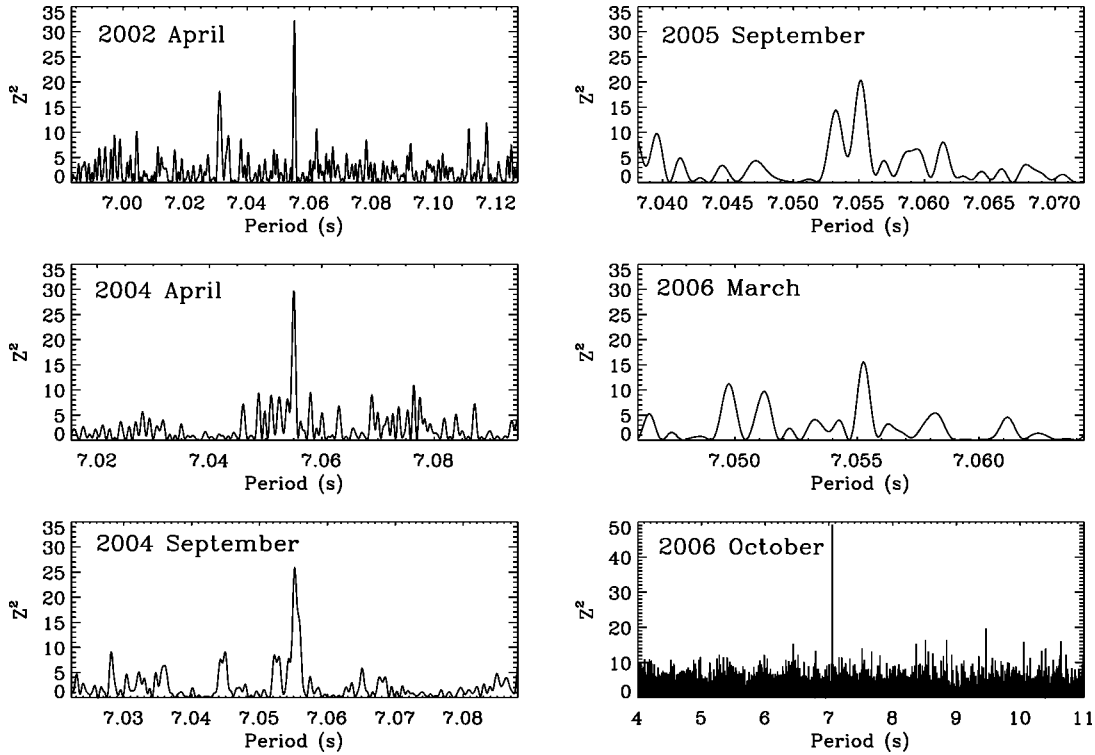


FIG. 2.—Distributions of the Z^2 -statistics for the *XMM-Newton* observations of RX J1856.5–3754. The period ranges shown in the first five panels correspond to those used in the period search and derived from a conservative \dot{P} assumption (see text for details).

is not particularly surprising. In fact, with about half a million counts, a $\sim 1\%$ modulation has a probability of 10% of giving a Z^2 as small as the observed value of 15.5 (Brazier 1994).

The best periods and pulsed fractions, determined in each observation as described above for the 2006 October data, are given in Table 1, while the folded light curves are presented in Figure 3. Although this figure seems to suggest some variations in the pulse profiles, we verified by means of a Kolmogorov-Smirnov test that, taking into account the unknown relative phase alignment, all the light curves are fully compatible with the same profile. We determined the relative phase shifts of the six observations by fitting sinusoidal functions to the folded light

curves. After applying these shifts, we summed all the pn and MOS data taken in small window mode to obtain the averaged light curves shown in Figure 4 for the total (0.15–1.2 keV), soft (0.15–0.26 keV), and hard (0.26–1.2 keV) energy ranges. The corresponding pulsed fractions are $1.17\% \pm 0.08\%$, $0.88\% \pm 0.11\%$, and $1.5\% \pm 0.11\%$.

All the period measurements, spanning more than 4 yr, are consistent with an average value of $P = 7.05515 \pm 0.00004$ s. With a linear fit to the period values we can limit the period derivative to $-1.2 \times 10^{-12} \text{ s s}^{-1} < \dot{P} < 1.9 \times 10^{-12} \text{ s s}^{-1}$ (90% c.l.).

We searched for the RX J1856.5–3754 pulsations also in the long *Chandra* observation performed with the LETG/HRC-S instrument in 2001 October. Our search, based on about 91,600 counts extracted from the zero-order image, gave a negative

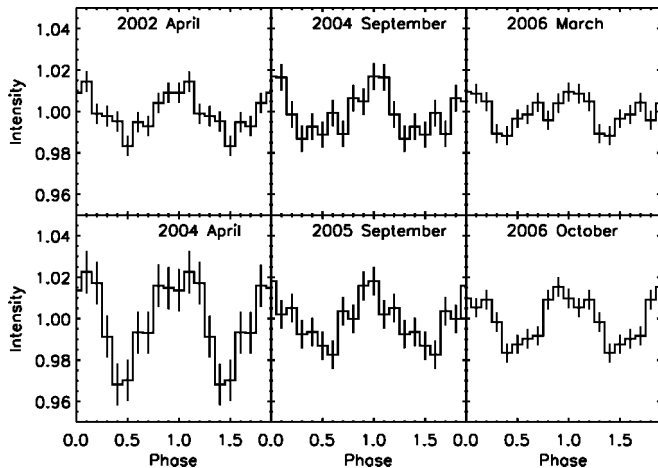


FIG. 3.—Background-subtracted light curves of RX J1856.5–3754 folded at the best-fit periods (see Table 1). The light curves are normalized to the average count rate. The phase alignment between the different panels is arbitrary. All the light curves are from the sum of pn and MOS counts in the 0.15–1.2 keV range, except for the 2004 April observation where only the 0.28–1.2 keV pn counts have been used.

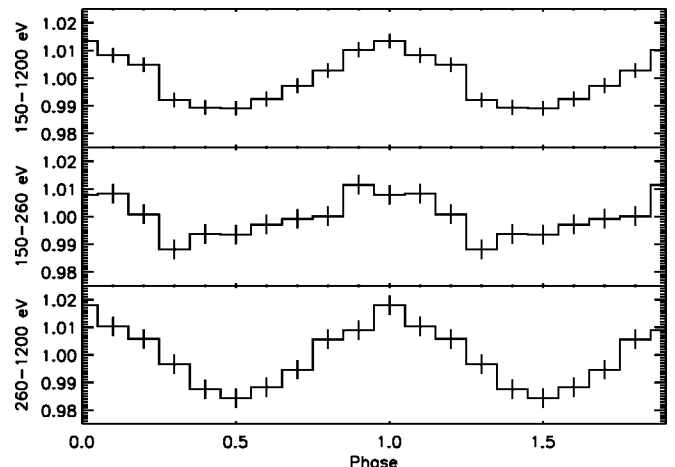


FIG. 4.—Light curves of RX J1856.5–3754 in the total (0.15–1.2 keV), soft (0.15–0.26 keV), and hard (0.26–1.2 keV) energy ranges obtained by summing all the pn and MOS data in small window mode.

result. This is not surprising, since for this number of counts and a $\sim 1.2\%$ pulsed fraction, the expectation value for the Z^2 -statistics is only 6.6. Furthermore, the long time span of the observation yields an intrinsic frequency resolution a factor of 10 better than that of the best *XMM-Newton* observation. This means a tenfold increase in the number of statistically independent periods that have to be examined and thus a higher threshold for a significant detection.

3. CONCLUSIONS

Our discovery of the long sought periodicity in RX J1856.5–3754 and the upper limit derived for \dot{P} can be used to infer a characteristic age $\tau > 6 \times 10^4$ yr, a magnetic field $B < 1.2 \times 10^{14}$ G, and a spin-down luminosity $< 2 \times 10^{32}$ ergs s $^{-1}$. These values are fully consistent with those of the other six XDINSs.

The pulsed fraction of RX J1856.5–3754 is significantly smaller than that of the other members of the group, which have pulsed fractions in the range from 4% to 18%. The *XMM-Newton* data also give evidence for a pulsed fraction increasing as a function of the energy. The small pulsed fraction in RX J1856.5–3754 might simply result from geometrical orientation effects or by a particularly small gradient in the surface temperature distribution. Detailed phase-resolved spectral mod-

eling, which might discriminate between the different possibilities, will be reported elsewhere. Here we simply note that the 2006 October pn spectra for the maximum and minimum of the folded light curve are both consistent with the best-fit absorbed blackbody model of the phase-averaged spectrum, simply rescaled in normalization. Letting all the fit parameters free to vary, the maximum allowed difference in the temperatures of the two spectra is of $kT_{\text{BB}} = 1.2$ eV (at the 90% c.l.). Repeating the same exercise for five phase bins, we find again no significant spectral variations, with all the parameters within the following ranges: $N_{\text{H}} = (4\text{--}8) \times 10^{19}$ cm $^{-2}$ and $kT_{\text{BB}} = 61.4\text{--}63.2$ eV.

Our results indicate that, except for the striking absence of deviations from a pure blackbody in its X-ray spectrum, RX J1856.5–3754 shares most of the properties of the other members of the XDINS group. More importantly, the discovery of pulsations opens the way for the determination of the timing-dependent parameters that are crucial for a more detailed modeling of the star's surface emission properties.

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