PERIODICITY SEARCH IN THE X-RAY DATA OF RX J0007.0+7302

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(Received 4 June 2004; accepted 29 June 2004)

Abstract. Some unidentified EGRET sources have been reported to have probable X-ray counterparts. Periodicities in the X-ray data of those sources, if found, may help to strengthen the identification and to reveal their nature. We performed a detailed search of periodicities with a photon-counting method, the H-test, in the XMM and ASCA data of RX J0007.0+7302, which is the most probable X-ray counterpart to the EGRET source 3EG J0010+7309. Although no periods with enough significance were found, a possible one, at 0.1275433±0.0000001 s (MJD 52327.03399), is quite intriguing based on results of cross-checking the two data sets. We suggest future analysis with other data to search the vicinity of this period.

Keywords: stars: individual (RX J0007.0+7302, 3EG J0010+7309), stars: neutron

1. Introduction

The nature of the gamma-ray source 3EG J0010+7309 (the 3rd EGRET catalogue, Hartman et al., 1999) remains unknown since its discovery by ERGET in early 1990s (in the 1st EGRET catalogue, GRO J0004+73: Fichtel et al., 1994; in the 2nd EGRET catalogue, 2EG J0008+7307: Thompson et al., 1995). Just like other members of the unidentified EGRET sources, the key to the understanding of their nature is their identification in other energy bands. The X-ray source RX J0007.0+7302, located near the center of the supernova remnant CTA 1, was proposed to be the counterpart to 3EG J0010+7309 (Slane et al., 1997; Brazier et al., 1998) based on the position coincidence and their consistency of being neutron stars. This connection was further strengthened by the spectral continuity from X-ray to gamma-ray bands (Slane et al., 2004). However, to firmly establish this identification, a conclusive evidence is a common period, presumably of the stellar rotation, in different energy bands. If such a period can be found, not only the identification is confirmed, but also its nature can be understood in the framework of gamma-ray pulsar theory. There are other similar proposals of identifying unidentified EGRET sources to neutron-star-like X-ray sources, such as 3EG J1835+5918 to RX J1836.2+5925 (Reimer et al., 2001; Halpern et al., 2002) and 3EG J2020+4017 to RX J2020.2+4026 (Brazier et al., 1996; Uchiyama et al., 2002).

These sources are also candidates of radio-quiet neutron stars. If they are confirmed to be gamma-ray pulsars, they will join the Geminga pulsar to form a class

Astrophysics and Space Science **297:** 361–367, 2005.

of radio-quiet rotation-powered pulsars. Their spin-down behavior may help us to understand why they are radio-quiet and why other radio-quiet isolated neutron stars do not emit gamma-rays at a detectable level.

In this paper we report the results of a periodicity search in the ASCA and XMM data of RX J0007.0+7302. Timing analysis has been performed with these two data sets separately, both using the fast Fourier transform without any detection (Slane et al., 1997, 2004). We applied a photon-counting method, the H-test (De Jager et al., 1989), in our analysis with trial periods at steps of a small fraction of the corresponding Fourier width over the period range 0.1–1000 s. Several tempting features were found from cross-checking the ASCA and XMM data sets. Based on the inferred characteristic age and spin-down power, we suggest the one at 0.1275433 ± 0.0000001 s (MJD 52327.03399) be the most likely one.

2. Data Analysis and Results

The XMM data of RX J0007.0+7302 that we used in the analysis is the one from the 40-ks observation performed on 2002 February 21. Since our purpose was periodicity search, only the data obtained with the pn detector in the small window mode, whose time resolution is about 6 ms, was employed. Standard selection procedure was conducted using the science analysis system (SAS) package. We picked events within a $10''$-radius circle centered at (J2000) RA $= 00^h07^m02^s.2$, DEC $= +73°03'07''$ (Slane et al., 2004). Events were further restricted in the energy band of 0.2–12 keV. The resultant total number of photons is 1106 and the exposure time is about 28 ks. The solar system barycentric time correction was performed to yield an event time list for analysis.

The ASCA data we used is GIS data from the observation on 1996 January 25. Time resolutions of that data are about 4 ms for the medium bit rate one and about 15 ms for the high bit rate one. In the archival screened data, which have been processed with standard screening criteria, RX J0007.0+7302 is buried in the diffuse X-ray emission of CTA 1. We therefore selected photons within a circle of a smaller radius, $1'.5$, centered at (J2000) RA $= 00^h07^m01^s.1$, DEC $= +73°03'07'$, which was inferred from interpolating between the XMM (Slane et al., 2004) and the ROSAT positions (Brazier et al., 1998; Seward et al., 1995). Photons in 0.5–10 keV were selected. The resultant exposure time is about 44 ks for both GIS2 and GIS3 data, and the total number of photons is 377 for GIS2 and 443 for GIS3. Barycentric time correction was performed with the task timeconv in the HEASOFT package. In the following analysis, data of GIS2 and GIS3, and of high and medium bit rate, are all combined together into a single time list.

Upon the two lists (from XMM and ASCA) of photon arrival times, we conducted a complete search with the H-test over the period range 0.1–1000 s, in the sense that trial periods were separated at a small fraction of the corresponding Fourier width, $P^2/2T$, where P is the trial period and T is the total time span

TABLE I
Trial periods at which the H value is larger than about 35

XMM period (s)	H value	r.p.	ASCA period (s)	H value	r.p.
0.11200955	37.9	9.04×10^{-7}	0.108139845	42.6	2.49×10^{-7}
0.13397840	36.0	1.57×10^{-6}	0.126403815	43.7	1.87×10^{-7}
0.14692094	39.8	5.27×10^{-7}	0.127512095	39.4	5.92×10^{-7}
0.17767572	33.9	2.91×10^{-6}	0.14237634	37.8	9.22×10^{-7}
0.4368722	39.5	5.76×10^{-7}	0.28658588	36.6	1.32×10^{-6}
0.8765945	34.9	2.16×10^{-6}	0.8096734	37.8	9.33×10^{-7}

Periods are reported with digits accurate to about one tenth of corresponding Fourier widths The random probability (r.p.) is for one single trial only. The total number of trials is not taken into account.

of the data (40 ks for XMM, 83 ks for ASCA). The total number of independent trials in this period range is about 8×10^5 for XMM and 1.66×10^6 for ASCA respectively.

Since we have performed such a complete search with a huge number of trials, it is rather difficult to find signatures of periodicities with enough significance. For example, the highest value of the H-statistics found in our search, 43.7, is in the ASCA data at the trial period 0.126403815 s. (As in Table I, trial periods are reported with digits accurate to about one tenth of their corresponding Fourier width. This should not be understood as the uncertainty level of a possible period, which can be determined, for example, from the χ^2 value in the epoch-folding method (Leahy, 1987).) The random probability for such an H value is 1.87×10^{-7} for a single trial. When taking into account the total number of trials, it will not be significant at all. The first result of our search, therefore, was that no signatures of periodicities were found in the XMM and ASCA data of RX J0007.0+7302.

However, tempting features may be found if one cross-checks both data sets. We first picked all the features with the H value higher than about 35, which corresponds to a random probability of 10^{-6}. Twelve such trial periods are listed in Table I; six from XMM and six from ASCA. Unfortunately, none of the twelve can be considered as relevant to any one from the other data set, since their difference implies too large a period derivative, which in turn would give too small a characteristic age less than a few hundred years. The age of the supernova remnant CTA 1 was estimated to be about 10,000 years (Sieber et al., 1981; Slane et al., 2004).

From the above twelve periods we further looked for their possible counterparts in the other data set based on two criteria: (1) only periods at which the H value is larger than 25 were considered and (2) the implied characteristic age is larger than 1000 years. Six such combinations were found and are listed in Table II. The period uncertainty is estimated based on the χ^2 value describing the deviation of its

TABLE II

Tentative counterpart periods in the ASCA and XMM data

Item	ASCA period (s)		XMM period (s)		$\dot{P}$ (10^{-13} s^{-1})
P1	0.11195598(3)	29.7	0.11200955(7)	37.9	2.794(4)
P2	0.12640382(4)	43.7	0.12662308(9)	28.1	11.436(5)
P3	0.12751210(4)	39.4	0.1275433(1)	29.7	1.625(6)
P4	0.13374106(5)	33.8	0.1339784(1)	36.0	12.379(6)
P5	0.2865859(3)	36.6	0.2869217(5)	25.2	17.52(3)
P6	0.4365495(7)	32.4	0.4368722(8)	39.5	16.83(6)

Numbers in parentheses are the 1-σ statistical uncertainties in the last digit. Numbers following each period are the associated H values. The $\dot{P}$ is derived from the two periods. The ASCA periods are at epoch MJD 50107.83546 and XMM at MJD 52327.03399.

folded pulse profile from a flat distribution with the prescription in Leahy (1987), $\sigma_P/\Delta P = 0.71(\chi_r^2 - 1)^{-0.63}$, where $\Delta P = P^2/2T$ is the Fourier width.

We have also compared their pulse profiles to study their similarity. Pulse profiles were folded at corresponding periods with 20 bins. A χ^2-test was applied to assess the probability of the two counterpart profiles being consistent with each other (e.g. Press et al. 1992). An arbitrary shift in phase was allowed since the uncertainty in keeping the phase for such a six-year time span was already much larger than one period. These results together with inferred characteristic ages and spin-down powers are listed in Table III. The two sets of pulse profiles with higher significance of similarity are plotted in Figures 1 and 2.

TABLE III

Properties of the six tentative counterpart periods

				Similarity test	
Item	XMM period (s)	τ_c (yr)	$\dot{E}$ (erg s^{-1})	χ^2	r.p.
P1	0.11200955(7)	6350	7.85×10^{36}	38.6	0.75%
P2	0.12662308(9)	1750	2.224×10^{37}	34.8	2.11%
P3	0.1275433(1)	12430	3.09×10^{36}	26.0	16.78%
P4	0.1339784(1)	1710	2.032×10^{37}	31.3	5.35%
P5	0.2869217(5)	2590	2.93×10^{36}	27.0	13.66%
P6	0.4368722(8)	4110	7.97×10^{35}	35.2	1.90%

$\tau_c = P/2\dot{P}$ is the characteristic age, $\dot{E}$ is the estimated spin-down power, and the χ^2 value is for the similarity test of the ASCA and XMM pulse profiles. r.p. is the corresponding random probability of the χ^2-test. The XMM periods are at epoch MJD 52327.03399. The 1-σ uncertainty level in τ_c and $\dot{E}$ propagating from that in P and $\dot{P}$ is to the last significant digit.

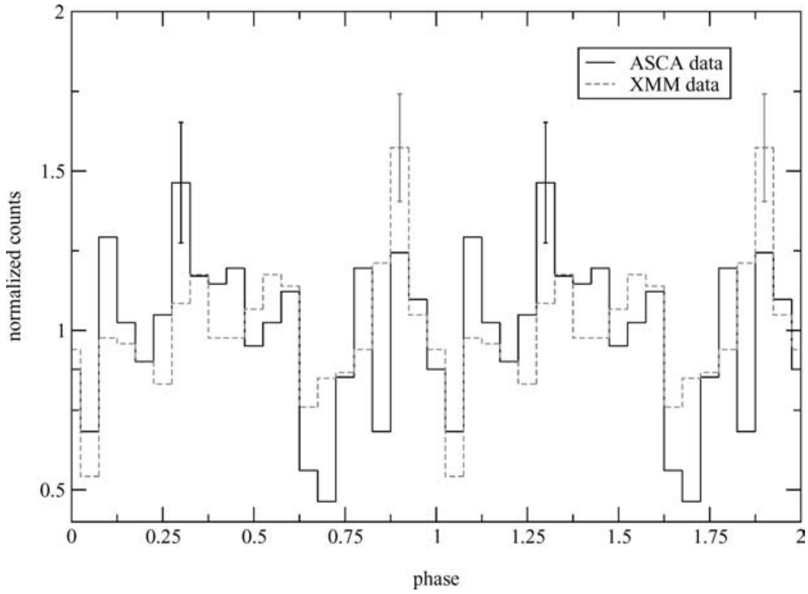

Figure 1. Pulse profiles of ASCA data folded at 0.127512095 s and XMM data at 0.127543255 s. It corresponds to item P3 in Tables II and III.

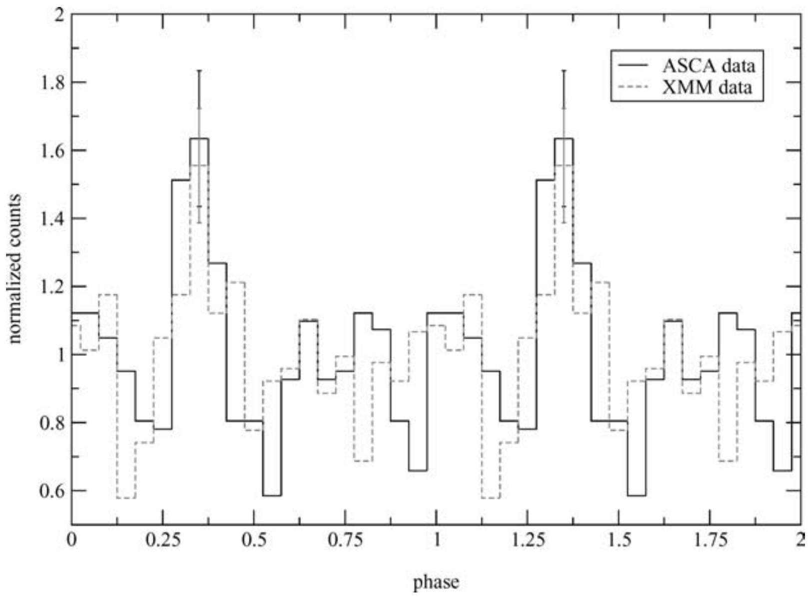

Figure 2. Pulse profiles of ASCA data folded at 0.286585876 s and XMM data at 0.286921721 s. It corresponds to item P5 in Tables II and III.

3. Discussion

We have performed a complete search for periodicities over the period range of 0.1–1000 s with the H-test. From cross-checking the ASCA and XMM data, Some tempting periods were found. The ASCA observation was on MJD 50107.83546 (the mid-point of the whole observation) and XMM on MJD 52327.03399. The characteristic age and estimated spin-down power $\dot{E} = 4\pi^2 I\dot{P}/P^3$, where I is taken as 10^{45} g cm^2, for all these cases are listed in Table III.

Item P3 in Table III deserves particular attention. Its characteristic age is close to that estimated in the literature (Sieber et al., 1981; Slane et al., 2004), its spin-down power is similar to that of the Vela pulsar and PSR B1706-44, which also have a similar characteristic age, and its ASCA and XMM pulse profiles show significant similarity (Figure 1). The spin-down power of RX J0007.0+7302 was estimated to be 1.7×10^{36} erg s^{-1} in Slane et al. (1997), based on an empirical relationship between the X-ray luminosity (0.2–4 keV) of the pulsar-powered plerion (plus the pulsar itself) and the pulsar spin-down power, $\log L_X = 1.39 \log \dot{E} - 16.6$ (Seward & Wang 1988). On the other hand, using another empirical relationship between the photon spectral index of the nonthermal X-ray emission from a pulsar and its spin-down power, $\Gamma = 2.08 - 0.029\dot{E}_{40}^{-1/2}$ (Gotthelf 2003), with the photon index Γ being 1.5 (Slane et al. 2004), we obtain an estimate of $\dot{E} \approx 2.5 \times 10^{37}$ erg s^{-1}. All the inferred spin-down powers in Table III, except item P6, are between these two empirical estimates.

We note that, for gamma-ray pulsars, younger ones tend to have stronger spin-down powers. For example, the two young gamma-ray pulsars, the Crab pulsar and PSR B1509-58, with a characteristic age of $10^{3.1}$ and $10^{3.2}$ years have spin-down powers of $10^{38.7}$ and $10^{37.3}$ erg s^{-1}, respectively. The Vela pulsar, PSR B1706-44 and PSR B1951+32 have a characteristic age of 10^4–10^5 years and spin-down power of a few times 10^{36} erg s^{-1}. In line of this consideration, items P5 and P6 seem unfavored. But item P5 has noticeable similarity between its ASCA and XMM profiles (Figure 2). The characteristic age and spin-down power in items P2 and P4 are both very similar to that of PSR B1509-58. Furthermore, the supernova remnant G320.4-1.2 (MSH 15-52), which is believed to be associated with PSR B1509-58, is also estimated to be much older than the characteristic age of PSR B1509-58 (Seward and Harnden, 1982; Seward et al. 1983; van den Bergh and Kamper, 1984). However, the significance level of the similarity between the ASCA and XMM pulse profiles is not high for these two cases. The spin-down property of item P1 is just between the young gamma-ray pulsars and the middle-aged ones. The similarity of its pulse profiles seems low.

The gamma-ray emission of 3EG J0010+7309 peaks at 1–2 GeV (in terms of power per decade) and drops off beyond 2 GeV (Brazier et al., 1998). If it is a gamma-ray pulsar, it would be more Vela-like than Crab-like. It again supports the period in item P3 being the most probable one. We suggest future timing analysis to search periodicities around these period candidates, particularly around the one in item P3.

Acknowledgements

This work was supported by the National Science Council of the Republic of China through grant NSC 92-2112-M-007-024.

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