International Journal of Engineering, Mathematical and Physical Sciences
ISSN: 2517-9934
Vol:6, No:10, 2012

# X-ray Pulse Profiles of PSR J0538+2817

Kun Tao Zhao, Na Wang, and Jian Ping Yuan

***Abstract*—**This paper reports our analysis of 163 ks observations of PSR J0538+2817 with the Rossi X-Ray Timing Explorer (RXTE).The pulse profiles, detected up to 60 keV, show a single peak asin the case for radio frequency. The profile is well described by one Gaussians function with full width at half maximum (FWHM) 0.04794. We compared the difference of arrival time between radio and X-ray pulse profiles for the first time. It turns out that the phase of radio emits precede the X-ray by 8.7 ± 4.5 ms. Furthermore we obtained the pulse profiles in the energy ranges of 2.29-6.18 keV, 6.18-12.63 keV and 12.63-17.36 keV. The intensity of pulses decreases with the increasing energy range. We discuss the emission geometry in our work.

***Keywords*—**RXTE, X-ray pulsars, PSR J0538+2817.

## I. Introduction

PSR J0538+2817, which located 40' Northwest of the geometric center of the supernova remnant S147 (G180.0-1.7), was discovered in an untargeted pulsar survey using the Arecibo radio telescope[1]. Its period and period derivative is $P = 0.143$ s and $\dot{P} = 3.6681\times10^{-15}$ ss$^{-1}$ respectively (see more radio ephemeris in Table I [2]). This is a middle-aged pulsar with $\tau_c = P/(2\dot{P}) \cong 6.2\times10^{5} yr$, and magnetic field strength $B = \sqrt{\frac{3c^3 I}{8\pi R^6} P\dot{P}} \cong 7.3\times10^{11}$. "Middle-aged" implies it is so old that its magnetospheric emission is fainter than the thermal emission, however, they are not too old to emit thermal radiation in the X-rays.

For PSR J0538+2817, the X-ray emissions consist of two components. One is the thermal emission from pulsar's hot surface. The other is nothermal emission from the effects of curvature, synchrotron, or inverse Compton radiation of the relativistic particles which accelerated by electromagnetic field. According to the age of PSR J0538+2817, the thermal emission is positively dominated. Except PSR J0538+2817, thermal emission from the pulsar's surface has been observed for three other pulsars: they are Geminga, PSR B0656+14, and B1055-52 [3].

K. T. Zhao is with Xinjiang Astronomical Observatory, Chinese Academy of Sciences, 150 Science-1 Street, Urumqi, Xinjiang 830011, China and Graduate University of Chinese Academy of Sciences, 19A,Yuquan Road, Beijing 100049, China (e-mail: kt.zhao@gmail.com).
N. Wang is with Xinjiang Astronomical Observatory, Chinese Academy of Sciences, 150 Science-1 Street, Urumqi, Xinjiang 830011, China (e-mail:na.wang@xao.ac.cn).
J. P. Yuan is with Xinjiang Astronomical Observatory, Chinese Academy of Sciences, 150 Science-1 Street, Urumqi, Xinjiang 830011, China (e-mail: yuanjp@xao.ac.cn).

TABLE I
EPHEMERIS OF PSR J0538+2817

| Parameter | Value |
|---|---|
| RAJ | $05^h\ 38^m\ 25.0572^s$ |
| DECJ | +28° 17' 09.161" |
| Pulse Period (P) | 0.14315825891177 s |
| Period Derivative (Pdot) | 3.6681e+05 ss$^{-1}$ |
| PEPOCH (MJD) | 51086.0 |
| Characteristic Age | 6.18e+05 yr |
| Edot | 4.9e+34 ergss$^{-1}$ |

X-ray emission of PSR J0538+2817 was first detected from the ROSAT all-Sky Survey [4], but neither timing nor spectral information was available. McGowan et al. [5] observed PSR J0538+2817 with XMM-Newton for 18 ks as a part of the Guaranteed Time Program. They found the pulse profile in 0.2-2 keV was broad and asymmetric. Their analysis show that the spectrum is well fitted with a blackbody with $T^{\infty} = (2.12^{+0.04}_{-0.03})\times10^{6} K$ and $N_H = 2.5\times10^{21} cm^{-2}$. Thus the X-ray emission was believed to be radiated from a heated polar cap.

Depends on Rossi X-ray Timing Explorer (RXTE)'s unprecedented 1µs time resolution, we should study the difference of arrival time of the pulses peaks between X-ray and radio for the first time. In this paper, we report on RXTE observations of PSR J0538+2817 and present the results of data analysis.

In the next section, we describe the observations and data reduction. In Sections 3, we present our analysis of pulse profile and the comparison of X-ray and radio profiles, and at last in Section 4, we discuss the physics implications of our results.

## II. Observations and Data Reduction

PSR J0538+2817 was observed by RXTE in 1997 with a total exposure for 18 ks. In this paper, we use the data from Proportional Counter Array (PCA) on-board RXTE [6] collected in "GoodXenon" mode, with Observing Id ranging from 20155-02-01-00 to 20155-02-01-060 (see Table II). The PCA consists of five Proportional Counter Units (PCUs) covering the energy range from 2 to 60 keV. In the "GoodXenon" mode, PCA records the arrival time of each photos with time resolution 0.9 µs in 256 channel resolution.

The data was downloaded from the High Energy Astrophysics Science Archive Research Center (HEASARC) at NASA's Goddard Space Flight Center. Data analysis was made by using version 6.10 of the FTOOLS package distributed by the HEAsoft [7].

First of all, the MAKETIME tool was run to make the good

ISSN: 2517-9934
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time intervals (GTI) for each data file, filtering parameters were: pointing OFFSET less than 0.02°, elevation (ELV) greater than 10°, at least 3 PCUs on, and time since the South Atlantic Anomaly at least 30 minutes. Then we used the FSELECT tool to filter out data outside these time ranges. For the best signal-to-noise ratio and the purposes of our analysis, we selected only top-layer data from each PCU.

TABLE II
RXTE OBSERVATIONS OF PSR J0538+2817:

| ObsID | Strat Time(1997) | Time Span(s) |
|---|---|---|
| 20155-02-01-00 | 16/03 09:23:06 | 11467 |
| 20155-02-01-01 | 16/03 17:54:00 | 1933 |
| 20155-02-01-02 | 17/03 09:25:10 | 14283 |
| 20155-02-01-03 | 20/03 06:39:14 | 21179 |
| 20155-02-01-04 | 18/03 11:04:06 | 11407 |
| 20155-02-01-05 | 18/03 21:19:00 | 28213 |
| 20155-02-01-06 | 19/03 12:42:06 | 6487 |
| 20155-02-01-07 | 20/03 00:03:19 | 2334 |
| 20155-02-01-08 | 20/03 01:46:17 | 15296 |
| 20155-02-01-040 | 18/03 03:30:17 | 27229 |
| 20155-02-01-060 | 19/03 06:13:16 | 23390 |

Next, we corrected photon arrival times (Terrestial Time, TT) to barycentric dynamical time (TDB) at the solar-system barycenter with the FAXBARY tool using the JPL DE200 solar system ephemeris and orbit file for those days.

After that, we extracted light curves from all available observations and converted them into the ASCII format for further processing.

## III. RESULTS

RXTE data were searched for pulse period by using the folding technique. A best period of 0.14285 s, which is very close to the radio period (Table I) was detected for PSR J0538+2817. The plot of the $\chi2$ versus the pulsar period show a clear single maximum (see Figure 1).

TABLE III
ENERGY RANGE OF EACH BAND

| Band | Energy range |
|---|---|
| Band 0 | 2.06 keV ~ 6.18 keV |
| Band 1 | 6.18 keV ~ 12.63 keV |
| Band 2 | 12.63 keV ~ 17.36 keV |

Then the light curves were folded to obtain pules profiles at the pulsar spin period given by Table I based on radio timing measurements. We use 32 phase bins for every spin period in which signal to noise ratios is high of the pulse profile.

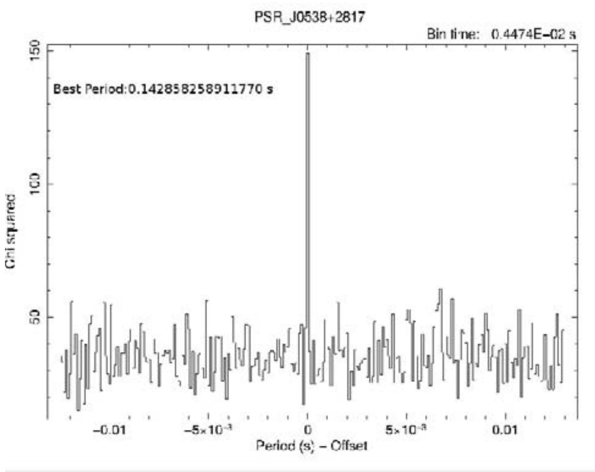


Fig. 1 Epoch folding $\chi2$ search for the pulse period of PSR J0538+2817 in the 2-60 keV RXTE PCA data

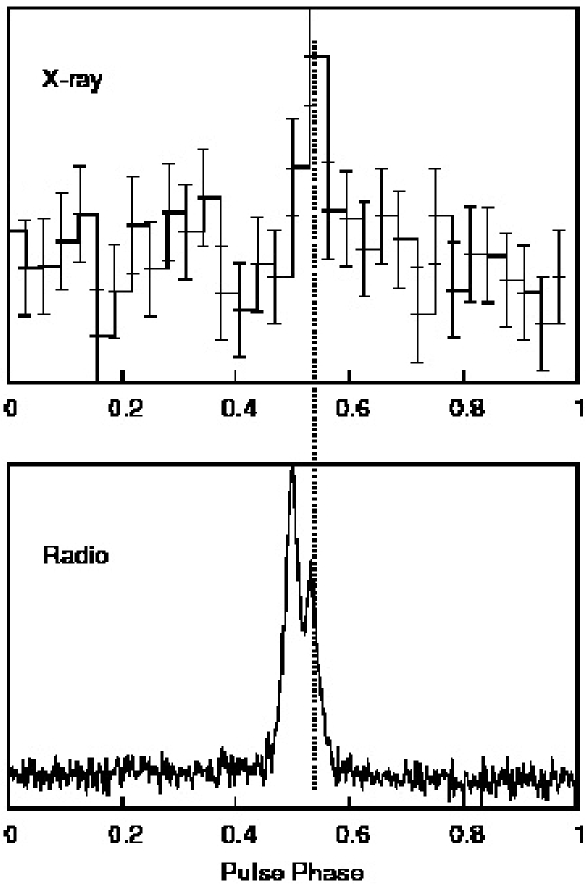


Fig. 2 Pulse profile of PSR J0538+2817 observed at 2-60 keV with RXTE PCA (top) and at 1.5 GHz with Nanshan 25 radio telescope (bottom). The phase are aligned in relative phase

The X-ray pulse profile (see Figure 2) shows some evidence of broader single peak compare to the radio profile. The radio pulse profile was observed at 1556MHz by the Nanshan 25m radio telescope.

We corrected the arrival times of radio pulses to barycentric arrival times, and compared with that of X-ray pulses. We calculate the time delay between the two peaks. The result shows that the peak of radio pulse arrives 8.7±4.5 ms earlier than that of the X-ray pulses.

The folded X-ray light curve is well fitted by a Gaussians function, with a pulse width (FWHM) ~0.04794 and 15% pulsed fraction.

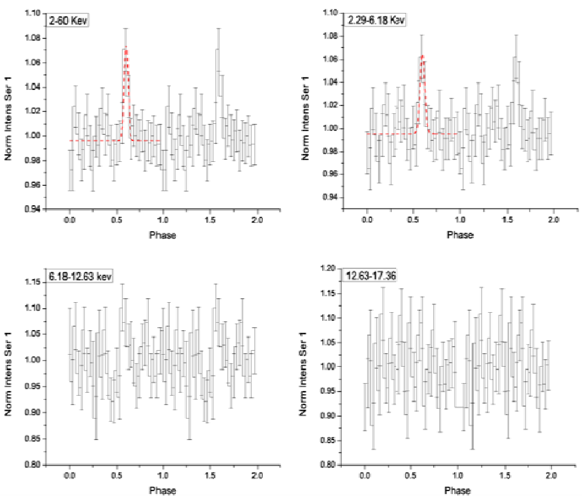


Fig. 3 Pulse profiles of PSR J0538+2817 observed by the RXTE PCA in the 2-60, 2.29-6.18,, 6.19-12.63, 12.63-17.36 keV energy window (32 bins). Two cycles are shown for clarity. The dashed lines show the best fitted Gaussian curve

In order to obtain the energy-dependent pulse profiles, we divided data into several energy bands according to Eenergy-Channel Conversion Table, in which the pulse profiles in the energy ranges of 2.29-6.18 keV, 6.18-12.63 keV and 12.63-17.36 keV (see Table III) were formed by folding the energy resolved signal. As shown in Figure 3, the power of the peak decreases with the increasing energy, and no obvious periodic pulsation was detected up to 20 keV. This analysis revealed that the X-ray emission is stronger at lower energy.

## IV. Conclusion and Discussion

In this paper, we have investigated the relationship between raido and X-ray pulse profiles of PSR J0538+2817. We dectected its X-ray pulses at the spin period. Both X-ray and radio revealed single pulse profile and in X-ray it is broader compared with the radio band. This might suggest that the radiation mechanisms between X-ray and radio band are correlated. The phase of the radio pulse leads the X-ray pulse by about $8.7\pm4.5$ ms. This implies that the geographical location of the radio and X-ray emission may be different. The region producing the X-ray emission probably preceed that producing the radio emission.

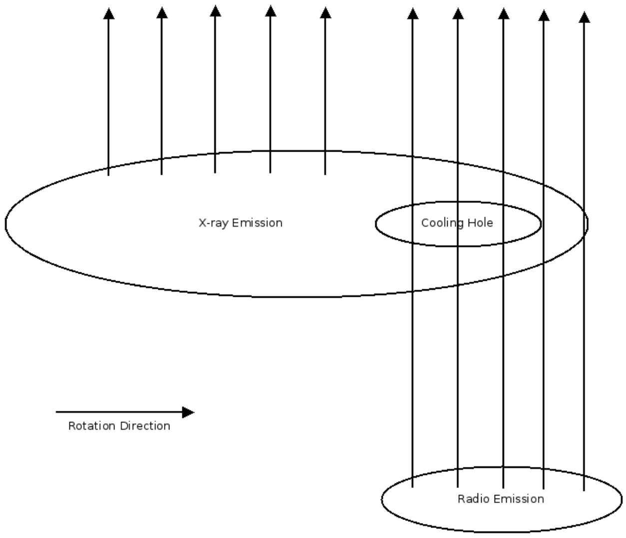


Fig. 4 Schematic diagram of the formation of cool hole

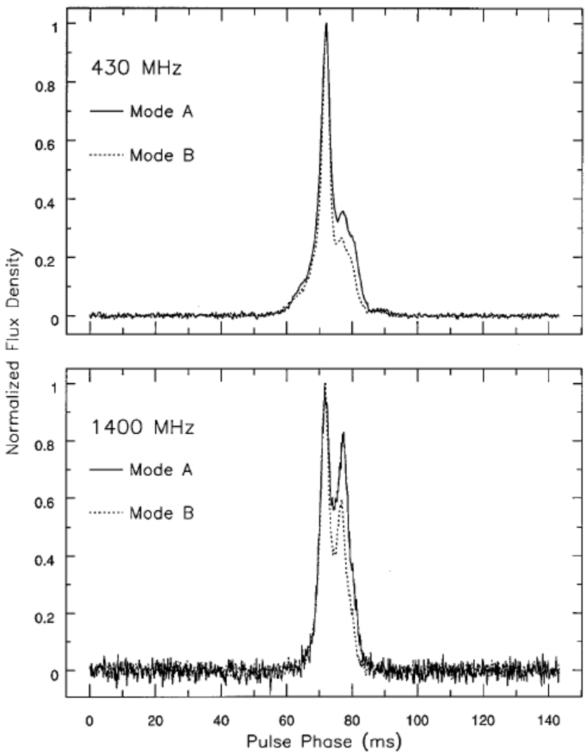


Fig. 5 Mode changing of PSR J0538+2817 provided by Anderson et al. (1996)

The pulse profiles provide proses to study the radiation geometry. Our analysis suggests that the shape of the X-ray pulse profile for PSR J0538+2817 is well fitted by a single Gaussian function, and it is not symmetrical with the leading wing of the peak has lower energy. Noticing that the left wing correspond to the peak of radio pulse. This may be attributed to that radio emission blew away the charged particles, thus the leading part of X-ray emission region is cooler than the trailing part (see figure 4). In other words, a 'cooling hole' formed in the leading part. Furthermore, radio observations by Anderson et al. [1] found mode changing phenomenon in PSR J0538+2817 (see Figure 5). The trailing part changing the intensity with normal mode A stronger than mode B. This might suggest a dynamic process that those particles being blown away fall back towards the surface now and then, which refrain the radio emission region.

It is widely accepted that the pulse intensity of X-ray pulsars are strongly dependent on the photon energy [8]~[11]. This may also be true for PSR J0538+2817. A significant change in the pulse intensity over energy band 2-60 keV is obversed. This behaviour is similar to the work presented by Frontera et al.[12] , and Nicastro et al. [13], where they attributed this energy dependence of the pulse profile to changes in the structure of emission origin.

In addition, we notice that the pulsation is not significant at the energy higher than 20 keV. This probably indicates that the thermal radiation is the main components of the observed energy, in which mechanism the higher energy radiation becomes weaker.

## ACKNOWLEDGMENT

Authors are grateful to High Energy Astrophysics Science Archive Research Center (HEASARC) of NASA. This work was supported by National Basic Research Program of China (973 Program 2012CB821801 and 2009CB824800) and Main Direction Program of Knowledge Innovation of Chinese Academy of Sciences ( KJCX2-YW-T09).

## REFERENCES

[1] S. B. Anderson, et al., "A 143 Millisecond Radio Pulsar in the Supernova Remnant S147," Astrophysical Journal Letters., vol. 468, pp. L55, Sept. 1996
[2] R. N. Manchester, et al., "ATNF Pulsar Catalog," AJ., 129, 1993-2006, Aug. 2005.
[3] W. Becker, and J. Trumper, "X-rays from millisecond pulsar," Astronomische Gesellschaft Abstract Series., No. 13, pp. 86, 1997.
[4] Sun, X., et al., "X-ray and gamma-ray observations of the pulsar PSR J0538+2817," International Conference on X-ray Astronomy and Astrophysics: R?ntgenstrahlung from the Universe., pp. 195-196, Feb. 1996.
[5] K. E. McGowan, et al., "Detection of Pulsed X-Ray Emission from XMM-Newton Observations of PSR J0538+2817," Astrophysical Journal., vol. 591, pp. 380-387, July 2003.
[6] K. Jahoda, et al., "In-orbit performance and calibration of the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA)," in Proc. SPIE, vol. 2808, pp. 59-70, Oct. 1996.
[7] J. K. Blackburn, "FTOOLS: A FITS Data Processing and Analysis Software Package," Astronomical Data Analysis Software and Systems IV, ASP Conference Series., vol. 77, pp. 367, 1995.
[8] A. A. Lutovinov, and S. S. Tsygankov, "Timing characteristics of the hard X-ray emission from bright X-ray pulsars based on INTEGRAL data," Astronomy Letters., vol. 35, pp.433-456, July 2009.
[9] K. Mukerjee, et al., "Energy dependence of x-ray pulse profile of the crab pulsar," Bulletin of the Astronomical Society of India., vol. 27, pp.181 1999.
[10] P. Meszaros, and W. Nagel, "X-ray pulsar models. I - Angle-dependent cyclotron line formation and comptonization," Astrophysical Journal., vol. 298, pp. 147-160, Nov. 1985.
[11] P. Meszaros, and W. Nagel, "X-ray pulsar models. II - Comptonized spectra and pulse shapes," Astrophysical Journal., vol. 299, pp. 138-153, Dec. 1985.
[12] F. Frontera, et al., "The X-ray pulsar A0535 + 26 - Pulse profile and its time variability in hard X-rays," Astrophysical Journal., vol. 298, pp. 585-595, Nov. 1985.
[13] L. Nicastro, et al., "The 2-10 keV emission properties of PSR B1937+21," in Proc. of the 270. WE-Heraeus Seminar on Neutron Stars, Pulsars, and Supernova Remnants., MPE Report 278., pp.87, 2002