Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Nuclear Physics B (Proc. Suppl.) 132 (2004) 596–599
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
www.elsevierphysics.com

The phase of the radio and X-ray pulses of PSR B1937+21

G. Cusumano[a], W. Hermsen[b], M. Kramer[c], L. Kuiper[b], O. Löhmer[d], E. Massaro[e], T. Mineo[a], L. Nicastro[a] and B.W. Stappers[f]

[a]Istituto di Astrofisica Spaziale e Fisica Cosmica - Sezione di Palermo, CNR, Via Ugo La Malfa 153, I-90146, Palermo, Italy

[b]SRON National Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

[c]University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL, UK

[d]Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

[e]Dipartimento di Fisica, Universitá La Sapienza, Piazzale A. Moro 2, I-00185, Roma, Italy; Istituto di Astrofisica Spaziale e Fisica Cosmica - Sezione di Roma, CNR, Via del Fosso del Cavaliere, I-00100 Roma, Italy

[f] ASTRON, Postbus 2, 7990 AA Dwingeloo, The Netherlands; Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

We present some results of an RXTE observation on PSR B1937+21, the fastest known millisecond pulsar ($P\simeq1.56$ ms). The pulse profile, detected up to ~20 keV, shows a double peak, with the main component much stronger than the other. The peak phase separation is 0.526 ± 0.002 and the pulsed spectrum over the energy range 2-25 keV is well described by a power law with a photon index equal to 1.14 ± 0.07. We find that the X-ray pulses are closely aligned in phase with the giant pulses observed in the radio band. This result suggest that giant radio pulses and X-ray pulses originate in the same region of the magnetosphere due to a high and fluctuating electron density that occasionally emits coherently in the radio band. The X-ray events, however, do not show any clustering in time indicating that no X-ray flares are produced.

1. INTRODUCTION

PSR B1937+21 was the first MSP discovered [1] and, with a period of 1.56 ms, it remains the most rapidly rotating neutron star presently known. The distance estimated from the observed dispersion measure (DM) and from a model for the Galactic free electron distribution [2,3] is 3.6 kpc. Its spin down luminosity is $\dot{E}\sim1.1\times10^{36}$ erg s^{-1} and the dipolar magnetic field component at the star surface is $\sim4.1\times10^{8}$ G. Like the Crab pulsar [4], PSR B0540−69 [5] and the other MSP PSR B1821−24, PSR B1937+21 exhibits sporadic emission of giant pulses in the radio band [6–8]. Such pulses are extremely short events ($\tau<0.3\ \mu s$) confined to small phase windows trailing the main and interpulse.

X-ray emission from this pulsar was detected by ASCA [9] above 2 keV, with a pulse profile characterized by a single sharp peak and a pulsed fraction of 44%. Comparing the X-ray and radio phase arrival times, these authors claimed that the X-ray pulse is aligned with the radio interpulse. Later, BeppoSAX detected pulsed emission from PSR B1937+21 [10,11] and the pulse profile was found to show a double peak pattern with a phase separation from P1 to P2 of 0.52 ± 0.04 and a significance of the second peak of $\sim5\ \sigma$. The BeppoSAX data did not allow to study the relative alignment between X-ray and radio pulses, because the timing did not maintain the necessary accuracy to UTC.

In this letter we present the results of the

0920-5632/$ – see front matter
doi:10.1016/j.nuclphysbps.2004.04.101

timing analysis of a RXTE observation on PSR B1937+21. We compare the absolute phases of the X-ray and radio pulsed signals and show that the X-ray peaks are phase aligned with the radio giant pulses.

2. PULSE PROFILE AND PHASE ANALYSIS

The RXTE observations were performed between February 22 and February 27, 2002. The total exposure times were about 140,000 s for the PCA units 0, 2 and 3, and about 20,000 s for the units 1 and 4. Standard selection criteria were applied to the observation data. We used only data obtained with the PCA [12] accumulated in "Good Xenon" telemetry mode for the timing and spectral analysis. Events are time-tagged with a 1μs accuracy with respect to the spacecraft clock and with an absolute time accuracy of 5-8 μs with respect to UTC. The UTC arrival times of all selected X-ray events were first converted to the Solar System Barycentre using the (J2000) pulsar position given in Table 1 and the JPL2000 planetary ephemeris (DE200, [13]).

The radio ephemeris of PSR B1937+21 were obtained from high precision timing observations made with the 100-m Effelsberg radiotelescope in Bonn, Germany, and with the Westerbork Synthesis Radio Telescope (WSRT) in Westerbork, The Netherlands.

Both sets of time of arrivals (TOAs) obtained at Effelsberg and WSRT were first independendly fit to a pulsar spin-down model with the software package TEMPO[1]. The resultant radio ephemerides were then used for aligning the RXTE data with the radio profiles, producing fully compatible results. Finally, we produced a best-fit timing model for PSR B1937+21 from the combined Effelsberg and WSRT TOAs to align the RXTE and radio data (see for more details [14]).

RXTE data were searched for pulsed emission by using the folding technique in a range centered at a value computed from the ephemeris reported in Table 1. The plot of the χ^2 vs the pulsar frequency showed a clear single maximum, very prominent above the noise level and the pulsar frequency, estimated by fitting the χ^2 peak with a gaussian profile, was $\nu = 641.92824453(2)$ Hz in agreement within the errors with that from the radio timing model.

The highest significance of the pulsation is reached in the energy interval 2.5–17.0 keV and the resulting X-ray pulse profile, obtained by folding the data with the radio frequency, is shown in Fig. 1 (top panel). It is characterized by a prominent narrow first peak (P1), and by a less apparent second peak (P2) with a significance of

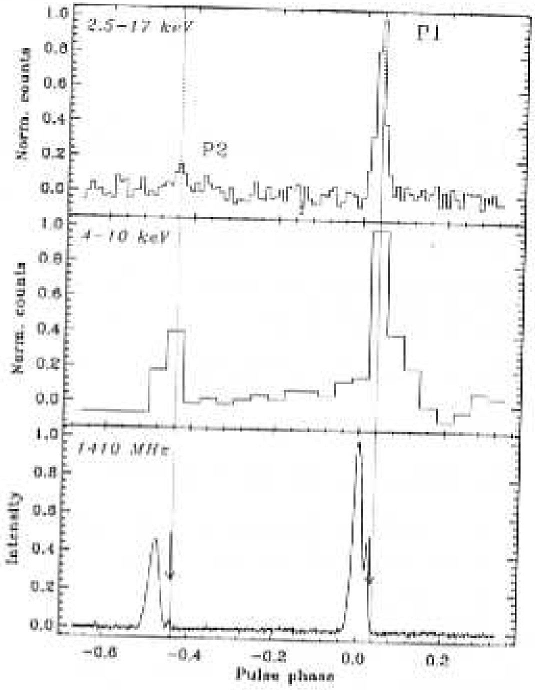

Figure 1. **Top:** The RXTE pulse profile of PSR B1937+21 in the 2-17 keV energy band. The bin size corresponds to ~ 16 μs. **Middle:** The 4-10 keV BeppoSAX profile [10] with the P1 aligned with the P1 phase in the top panel. **Bottom:** Radio pulse profile at 1.6 GHz obtained from Effelsberg. Vertical arrows indicate the phases of observed radio giant pulses.

[1] http://pulsar.princeton.edu/tempo

only 8σ above the off-pulse level. P2 is lagging P1 by 0.526 ± 0.002, determined by fitting both pulses with symmetric Lorentzian shapes. While the detection of P2 is weak, its presence is confirmed by the BeppoSAX observation [10]. We show the BeppoSAX result in the middle panel of Fig. 1: this profile has been shifted to align P1 with the phase of P1 in the top panel. Pulse widths are wider in the BeppoSAX data likely because the events are affected by a less accurate time tagging. The P1 width (FWHM) measured in the RXTE profile is only 29 ± 2 μs and the P2 width is 51 ± 21 μs. Fig. 1 (bottom panel) shows the radio profile from one Effelsberg observation. Vertical arrows mark the phases of giant pulses [8]. The comparison in absolute phase between the X-ray and radio profiles shows that the P1 lags the main radio pulse by $44 \pm 1 \pm 5 \pm 8$ μs and P2 lags the secondary radio peak by $51 \pm 3 \pm 5 \pm 8$ μs, where the quoted uncertainties reflect, first, statistical error, second, source position inaccuracies and third, the absolute time accuracy of RXTE. The X-ray peaks appear closely aligned with the phase of the radio giant pulses. In addition, the phase separation between the X-ray pulses of 0.526 ± 0.002 is more consistent with the phase separation between the positions of the giant radio pulses (0.5264 ± 0.0006) than with that between the radio main and secondary pulses (0.52106 ± 0.00003). The latter makes a systematic difference in the absolute X-ray and radio timing as explanation for the shifts unlikely.

The occurrence of the same phases for the X-ray pulses and the radio giant ones suggests the possibility that high energy photons are emitted simultaneous with the radio giant pulses. Therefore, we searched if there is some evidence for a bunching of X-ray photons with a rate similar to that of giant pulses and equal to $\sim$4 pulses per minute [7,8]. During the RXTE exposure we then expected that pulsed events occur in about 9000 X-ray flares. To investigate this hypothesis we made an X-ray light curve selecting only events within the phase interval centered in P1 with a phase width of $\Delta\phi = 0.06$ (90 μs) and studied the frequency distribution of these events. Since the dead time of the PCA is about 10 μs the maximum content of a bin in the presence of a X-ray flares can not exceed 8-9 counts. We found the following statistics: 2 bins with 4 counts, 11 bins with 3 counts, 574 bins with 2 counts, 294 060 bins with 1 count and 92 208 884 with 0 counts. This distribution is not consistent with the Poisson statistics, where the expected number of bins with a number equal or higher than 2 counts is much lower than measured. However, there is no evidence for the existence of X-ray giant pulses because the number of bins with a content different from the Poisson distribution was only 116, much lower than the number foreseen from the frequency of radio giant pulses. Another possibility is that the rate of X-ray giant pulses could be lower than that observed in the radio band and that the high energy emission could be a mix of stationary emission plus some more rare giant pulse episodes. We constructed other light curves selecting events in 10 different phase intervals far from P1 and P2 and with the same phase width used in the selection of the P1 interval. We found similar deviations from the expected Poisson distribution in all light curves. In particular, the number of bins deviating from a Poisson distribution was found to be between 60 and 150. Therefore, we conclude that there is no evidence that the X-ray emission of PSR B1937+21 is bunched in relatively rare events of high intensity.

3. DISCUSSION

The RXTE observations of the millisecond pulsar PSR B1937+21 provided for the first time a detection of a pulsed emission up to an energy of 20 keV. Like in the radio, we find a double peaked pulse shape with a dominant first peak and a much weaker second peak. Despite being only weakly detected, its presence is confirmed by recent BeppoSAX data showing a second peak at the exact same location. Our result is not in agreement with the single peak profile at the same phase of the radio interpulse, reported by [9] from ASCA data. The major finding of the present analysis is that the X-ray and radio pulses are not precisely aligned, but the former lags the latter by a phase difference of 0.04 ± 0.01, not large but significant. The X-ray pulses are then very well aligned to the giant pulses observed in the radio band [8]. The X-ray pulsed emission, however, is found to be stable, because we do not find evidence of any clustering in time, indicating that no X-ray flares are produced.

REFERENCES

1. Backer, D.C.,& Sallmen, S.T., Nature 300 (1982) 615
2. Taylor, J.H., & Cordes J.M., ApJ 411 (1993) 674
3. Cordes, J.M., Lazio, T.J.W., astro-ph/0207156 (2002)
4. Lundgren, S.C., Cordes, J.M., Ulmer, M., et al., ApJ 453 (1995) 433
5. Johnston, S., & Romani, R.W., ApJ, 590, L95 (2003)
6. Sallmen, S., & Bacher, D.C., in ASP Conf. Ser. 72, Millisecond Pulsars: A decade of Surprise, ed. A. S. Fruchter, M. Tavani, & D.C. Backer (San Francisco: AOP) (1995) 340
7. Cognard, I., Shrauner, J.A., Taylor, J.H., & Thorsett S.E., ApJ 457 (1996) L81
8. Kinkhabwala, A., & Thorsett, S.E., ApJ 535 (2000) 365
9. Takahashi, M., Shibata, S., Torii, K., et al., ApJ 554 (2001) 316
10. Nicastro, L., Cusumano, G., Kuiper, L., et al., Proceedings of the Seminar on Neutron Stars, Pulsars and Supernova Remnants, Physikzentrum Bad Honnef, eds W. Becker, H. Lesch & J. Trümper (2002)
11. Nicastro, L., Cusumano, G., Mineo, T., et al., A&A, submitted(2003)
12. K. Jahoda, et al., SPIE, 2808, 59 (1996)
13. Standish, E.M., A&A 114 (1982) 297
14. Cusumano, G., et al., A&A, in press, astro-ph/0309580 (2003)