PROCEEDINGS OF SCIENCE

Fast transitions between single and double-peaked optical pulse profiles of millisecond pulsar J1023+0038

A. S. Tanashkin,[a,*] **G. M. Beskin,**[b,c] **S. V. Karpov,**[d,b,c] **V. L. Plokhotnichenko,**[b] **Yu. A. Shibanov**[a] **and D. A. Zyuzin**[a]

[a] *Ioffe Institute,*
Politekhnicheskaya 26, St. Petersburg, 194021, Russia
[b] *Special Astrophysical Observatory, Russian Academy of Sciences,*
Nizhniy Arkhyz, Russia
[c] *Institute of Physics, Kazan Federal University,*
Kazan, Russia
[d] *CEICO, Institute of Physics, Czech Academy of Sciences,*
Prague, Czech Republic

E-mail: artyom.tanashkin@gmail.com

We report some results of optical observations of the transitional millisecond pulsar PSR J1023+0038, performed with the multi-channel panoramic photometer-polarimeter mounted on the 6-meter BTA telescope. The setup allowed us to register photons simultaneously in two channels ("red" and "blue") with the effective temporal resolution of about 1 μs. We detected optical pulsations at the pulsar frequency with characteristics similar to the ones reported in other studies. In addition, during one of the nights we observed dramatic change in the pulse profile structure, mainly characterized by fast transition from double-peaked to single-peaked shape and back, and accompanied by flaring activity of the system. We analyse the results and discuss some aspects of their physical interpretation regarding the origin of the pulsing emission.

The Multifaceted Universe: Theory and Observations - 2022 (MUTO2022)
23-27 May 2022
SAO RAS, Nizhny Arkhyz, Russia

*Speaker

PoS(MUTO2022)059

1. Introduction

PSR J1023+0038 (J1023 hereafter) is one of very few known transitional millisecond pulsars. These systems are characterized by transitions between two distinct states, one with properties of a low-mass X-ray binary system and the other similar to redback millisecond radio pulsars. Such transitions are believed to take place when the system approaches the last stage of the so-called recycling scenario, in which old neutron stars in binary systems are spun up to frequencies of hundreds of hertz via accretion and become millisecond radio pulsars.

J1023 revealed its nature in 2007, when a bright radio pulsar with a period of 1.67 ms was found [1] at the site of a low-mass X-ray binary with an orbital period of 4.75 h, which turned into quiescence a few years earlier. For six years, J1023 was observed as a typical redback pulsar, but then in June 2013 another transition occurred, and the system has remained in the low-mass X-ray binary state since then.

The unique observational property of J1023 is millisecond optical pulsations, first found by [2] and confirmed in subsequent studies (e.g. [3–5]). The pulse profile has two peaks with variable amplitudes, reaching about 1 percent in the maximum. Simultaneous multi-wavelength observations demonstrated a strong relation between optical pulsations and the activity of the system in X-rays [4].

2. Observations and data reduction

J1023 was observed during 7 nights in 2017–2020 with the multi-channel panoramic photometer-polarimeter mounted on the 6-meter telescope BTA of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). This instrument allowed us to register photons from the object with a time resolution of about 1 μs simultaneously in two channels based on two position-sensitive detectors (PSD), the "red" one with the GaAs photocathode ($\lambda_{\rm eff}$ = 5640 Å) and the "blue" one with the multi-alcali photocathode ($\lambda_{\rm eff}$ = 4170 Å) [6]. The total exposure is about 10 hours (see Table 1).

The times of arrival of photons were converted to the barycenter of the Solar System using DE405 ephemeris. We used the timing solution from [7] to obtain preliminary pulsar frequency and orbital phase to search for periodic signal. However, J1023 is known to exhibit chaotic orbital

Night	Date (MJD)	Exposure, s	Orbital phases
1	17.02.2017 (57801)	3800	0.31–0.54
2	14.11.2017 (58071)	3200	0.64–0.83
3	15.11.2017 (58072)	6700	0.46–0.91
4	07.04.2018 (58215)	3800	0.68–0.89
5	31.01.2019 (58514)	6000	0.54–0.89
6	04.01.2020 (58852)	8700	0.83–0.33
7	05.01.2020 (58853)	3300	0.32–0.52

Table 1: Summary of the BTA observations.

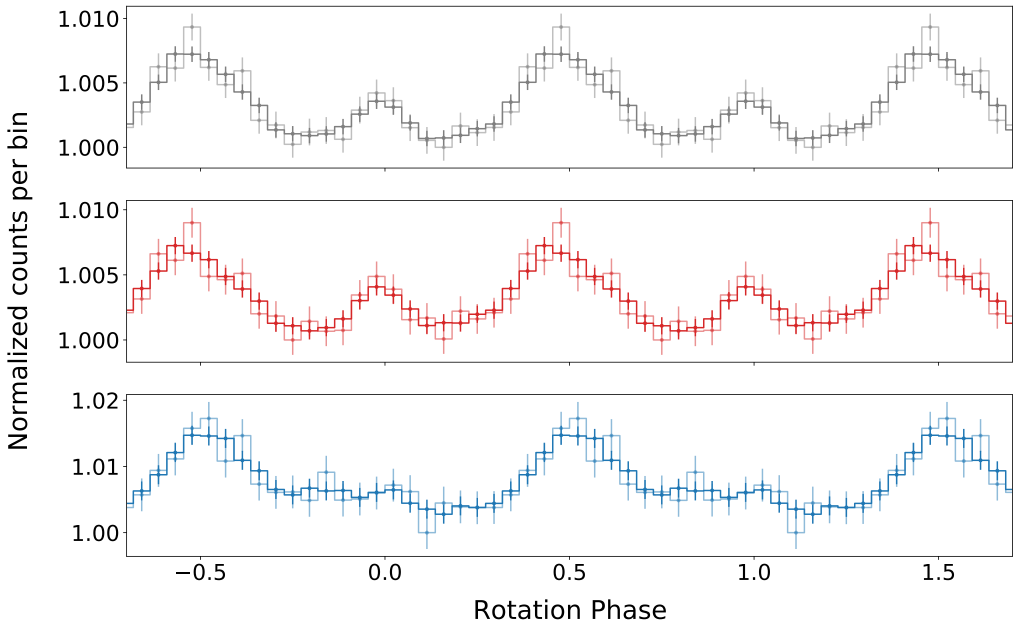

Figure 1: Pulse profiles of J1023 after orbital phase optimization during the fifth night in both channels joined (top), only red (middle) and only blue channel (bottom). The observed profiles are shown with pale step plots, while bold lines correspond to the profiles smoothed with a sliding window 3 bins wide. The double-peaked structure typical for J1023 is clearly seen.

phase shifts around its ephemeris values, with a maximum amplitude of about 25 seconds. To account for such shifts, and to correctly convert the times of arrival of photons to the barycenter of the binary system, for every night we performed the standard optimization procedure (see, e.g., [7]), finding the value of the orbital phase which provides the maximum phase-folding statistics for a given pulsar frequency.

3. Results

In Figure 1 we present typical double-peaked pulse profiles obtained during one of the nights. Similar behavior is seen in the majority of our data. The amplitudes of the peaks are highly variable, sometimes pulsations disappear altogether, sometimes they become stronger, leading to a full night averaged background-corrected pulsed fraction of about 1 percent. The pulsed fractions in the blue channel are systematically slightly higher than in the red one. Estimations of the energy distribution in the pulsed component give a flat spectrum.

During the third night (Nov 15 2017) we observed fast transition from the double-peaked profile to the single-peaked one, and back (Fig. 2), with a characteristic timescale of $\lesssim$ 50 s. For about 230 seconds, the amplitude of pulsations in both channels greatly increased (from $\approx$ 0.5 percent to $\approx$ 2 percent), and the pulse shape became nearly sinusoidal. We note that this transition can not be explained only by amplification of the main peak and disappearance of the second one (compare

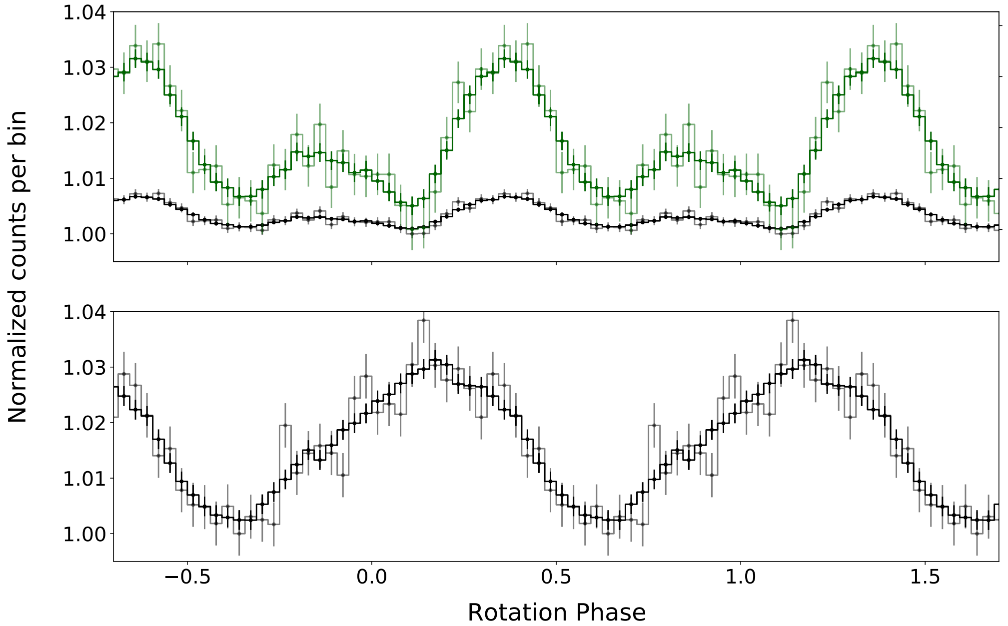

Figure 2: Upper panel: phase-folded 6.5-ks long light curve (joined channels) obtained from the full third night data except for the 230-s long interval with single-peaked pulsations. Black and green step plots show the same data in different scales (shown at the left and right borders, respectively) for illustrative purposes. Lower panel: the single-peaked interval. Note the increase of the amplitude compared to the black profile in the upper panel. In both panels, pale lines correspond to the observed profiles with 32 bins, while bold lines show the profiles smoothed with a 5 bin wide sliding window.

the rotation phases and widths of the peaks in the upper and lower panels of Fig. 2). Instead, the overall morphology of the pulse shape changed, which may indicate reconfiguration of the neutron star magnetosphere. Additionally, we detected fast flaring activity of the system during the event (see Fig. 3).

Chaotic orbital phase variations, reported in previous studies (e.g. [4, 7]), are also present in our data. Maximum orbital shifts of about 25 seconds correspond to linear displacements of the area responsible for the pulsing emission as large as 3000 kilometers. If real, such displacements pose serious problems for the models which consider transformation of the pulsar wind energy into optical emission near the light cylinder of the neutron star (e.g. [4, 8]). One of the possible alternatives could be a scenario of multiple clouds of matter scattered along the orbit, in which physical conditions favorable for the re-emission of the pulsar wind energy in the optical band are generated spontaneously.

4. Acknowledgements

This study is based on the data obtained with the unique scientific facility at the Big Telescope Alt-azimuthal of SAO RAS. The work of GMB, SVK and VLP was supported under

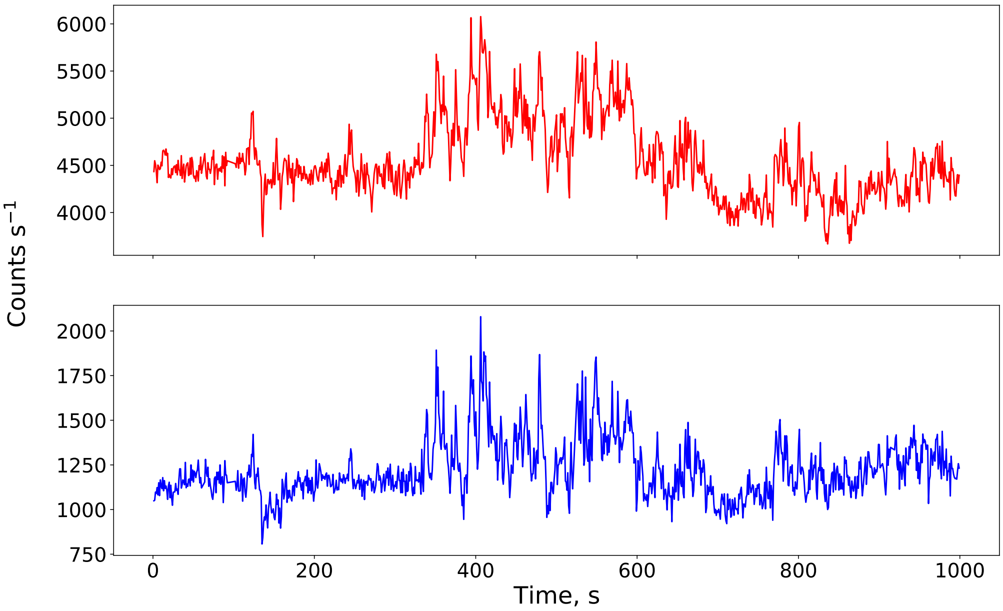

Figure 3: Background-corrected light curves of a 1-ks long data segment containing the interval with pulse shape changes. Red and blue channels are shown in the upper and lower panels, respectively. Flaring activity, evident in the 350–600 s range, roughly corresponds to the interval with strong single-peaked pulsations.

the Ministry of Science and Higher Education of the Russian Federation grant 075-15-2022-262 (13.MNPMU.21.0003).

References

[1] A.M. Archibald, I.H. Stairs, S.M. Ransom, V.M. Kaspi, V.I. Kondratiev, D.R. Lorimer et al., *A Radio Pulsar/X-ray Binary Link*, *Science* **324** (2009) 1411 [0905.3397].

[2] F. Ambrosino, A. Papitto, L. Stella, F. Meddi, P. Cretaro, L. Burderi et al., *Optical pulsations from a transitional millisecond pulsar*, *Nature Astronomy* **1** (2017) 854 [1709.01946].

[3] L. Zampieri, A. Burtovoi, M. Fiori, G. Naletto, A. Spolon, C. Barbieri et al., *Precise optical timing of PSR J1023+0038, the first millisecond pulsar detected with Aqueye+ in Asiago*, *MNRAS* **485** (2019) L109 [1903.08930].

[4] A. Papitto, F. Ambrosino, L. Stella, D. Torres, F. Coti Zelati, A. Ghedina et al., *Pulsating in Unison at Optical and X-Ray Energies: Simultaneous High Time Resolution Observations of the Transitional Millisecond Pulsar PSR J1023+0038*, *ApJ* **882** (2019) 104 [1904.10433].

[5] S. Karpov, G. Beskin, V. Plokhotnichenko, Y. Shibanov and D. Zyuzin, *The study of coherent optical pulsations of the millisecond pulsar PSR J1023+0038 on Russian 6-m telescope*, *Astronomische Nachrichten* **340** (2019) 607.

[6] V.L. Plokhotnichenko, G.M. Beskin, V.G. de Bur, S.V. Karpov, D.A. Bad'in, Z.V. Lyubetskaya et al., *High-temporal resolution multimode photospectropolarimeter*, *Astrophysical Bulletin* **64** (2009) 308.

[7] A. Jaodand, A.M. Archibald, J.W.T. Hessels, S. Bogdanov, C.R. D'Angelo, A.r. Patruno et al., *Timing Observations of PSR J1023+0038 During a Low-mass X-Ray Binary State*, *ApJ* **830** (2016) 122 [1610.01625].

[8] A. Veledina, J. Nättilä and A.M. Beloborodov, *Pulsar Wind-heated Accretion Disk and the Origin of Modes in Transitional Millisecond Pulsar PSR J1023+0038*, *ApJ* **884** (2019) 144 [1906.02519].