The study of coherent pulsations of optical emission of PSR J1023+0038 millisecond pulsar

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Abstract We observed the PSR J1023+0038 millisecond redback pulsar in its accreting regime on two nights in Nov 2017 on Russian 6-m telescope with a high temporal resolution panoramic photometer-polarimeter in two-channel (“blue” and “red”) setup. During 400 seconds of nearly 3 hours of total observations, we detected coherent optical pulsations in both color bands with 1.69 ms period, corresponding to the rotational period of neutron star known from radio data, with amplitudes of 2.1% (“red”) and 1.3% (“blue”). Corresponding luminosity of pulsed component is about 10^{31} erg/s and may be caused by a synchrotron emission of electrons with moderate Lorentz factors close to a light cylinder during the interaction of accretion disk with ejected matter modulated with rotational period.

Keywords: Neutron Stars, Accretion Processes, Millisecond Pulsars, High Temporal Resolution

1. Introduction

The first millisecond radio pulsar PSR B1937+21 was discovered in 1982 [1], and its nature was immediately explained in view of the concept of neutron star rotation speed-up during the accretion of matter from a companion star in a compact binary system [2]. However, the first direct confirmation of this model came much later, after discovery in 1998 of a SAX J1808.4-3658 spinning-up pulsar in a low-mass binary system [3]. Finally, three systems were found to contain a neutron star transitioning from accretion to ejection stages – PSR J1023+0038 [4], XSS J12270−4859 [5], and PSR J1824−2452I [6]. The most interesting (and mysterious!) is a 1.69 ms period PSR J1023+0038 pulsar – the component of FIRST J102347.6+003841 binary, initially thought to be a cataclysmic variable detected by its radio emission [7]. To date, it was twice observed switching the stage – from accretion to ejection in 2003 [4] and back to accretion in 2013 [8]. This object is a “redback” compact binary with a 4.75 hour period, containing a 0.2 $M_\odot$ G class normal component overflowing its Roche lobe, at a 1.37 kpc distance from the Earth [9]. X-ray and gamma-ray observations demonstrated the intensity variations with orbital period, interpreted as a manifestation of a shock wave at a collision region between pulsar wind and accreting matter [10]. Moreover, the X-ray emission was found to consist of three separate states – high (7 10^{33} erg/s), low (10^{33} erg/s) and flaring (10^{34} erg/s) with intensity variations on tens of seconds time scale, with state switching occurring rapidly and sporadically [11]-[14]. Coherent X-ray pulsations with neutron star rotational period of 1.69 ms are detectable only in high state [15], [16], in contrast to the optical ones which was detected in flaring state too [16], [17]. In optical and infrared bands PSR J1023+0038 also displays sporadic activity on seconds to hours time scales [18], [21]. The minimal variability time scale of optical emission is as fast as fractions of seconds [22], [23], which is close to the characteristic time scales of variability due to matter fragmentation in propeller regime in MHD simulations [24]. The discovery of coherent optical pulsations synchronous with X-ray ones and having a characteristic double sinusoidal pulse shape during the accretion stage was an extremely important and unexpected result [16], [17]. It was suggested that these multi-wavelength pulsations may be caused by a synchrotron emission of electrons in the region of collision of pulsar wind with accretion flow [16].

In the present work we report on detection of periodic pulsations on neutron star rotation time scale simultaneously in two optical bands during our observations with the Russian 6-m telescope in Nov 2017, and discuss its nature.

2. Observations and results

We observed the PSR J1023+0038 millisecond pulsar, which is currently in accretion stage, on Nov 14 and 15, 2017, with the Russian 6-m telescope using a panoramic photometer-polarimeter in the dual-channel regime, using two MCP-based panoramic photon counters (the “red” one with the GaAs photocathode on 5640A effective wavelength, and the “blue” one with the multi-alcali photocathode on 4530A effective wavelength) to detect and register all photons in a 10″×10″ diaphragm around the object [25]. Total duration of observations was about 3 hours (1 hour at the first night, 2 hours at the second night), effective temporal resolution was 1 us. The times of arrival of every photon were converted to the Solar system barycenter, and then corrected for the orbital motion in the object binary system using the timing solution published in [26], adjusting the epoch of ascending node by 25.6 seconds by maximizing the phase-folding χ^2 analogous to the method using in [16], [27].

Time-resolved spectral analysis of the corrected data revealed a single 400 seconds long interval with significant (the peak significance is better than 10^{-16}) oscillations around rotational frequency of a neutron star. All other data intervals lack any peak there. Time-resolved phase folding using timing solution from [26] also revealed a single pulsed activity interval only (see Figure 1, Figure 2 and Figure 3).

Figure 4 shows the phase folded light curves in both colour bands over this time interval. The shape of folded light curves is nearly sinusoidal, in contrast with a two-peak one seen by [16], [17], [27]. Amplitudes of the pulsations after correction for the background flux contribution are A_R=2.1% in the “red” channel and A_B=1.3% in the “blue” band, with A_B/A_R = 0.61 (0.376 – 0.878 for 95% confidence interval), which, according to the optical spectrum of the object [16] and the throughput curves of channels, corresponds to absolute fluxes F_B=14.6±3 and F_R=6.8±2.6 microJansky. Therefore, for a distance to the object of 1.37 kpc [9], the optical luminosity of pulsed component is about 10^{31} erg/s with an accuracy of about 30%. Assuming the power law spectrum $F_\nu \sim \nu^{-\beta}$ for a pulsed component, its slope is β=3.5 (1.4 – 5.1 for the 95% confidence interval).

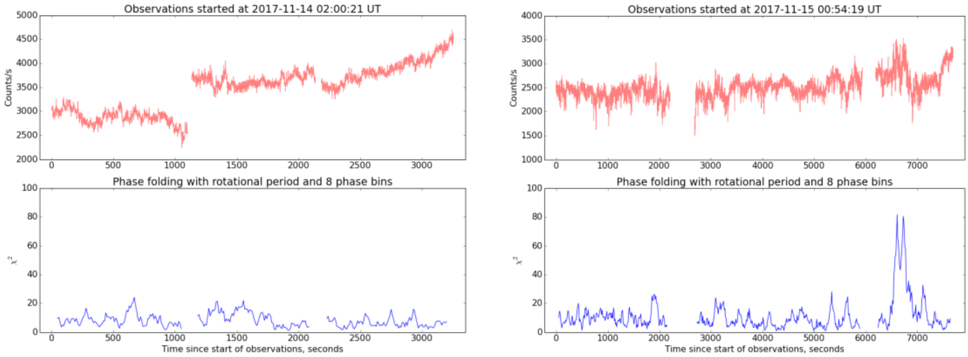

Fig1. *Overall light curves for data from the "red" detector (up) and phase-folding* χ^2 *(down) using [26] timing solution in 100 s wide sliding windows. Left panel: data from the night on Nov 13, 2017. Right panel: data from the next night, Nov 14, 2017. Gaps separate continuous intervals of observations (data segments). Telescope pointing was adjusted between these observations, which explains the intensity jump on Nov 14. Only a single 400 seconds long interval in the last data segment contains significant pulsations on neutron star rotational period.*

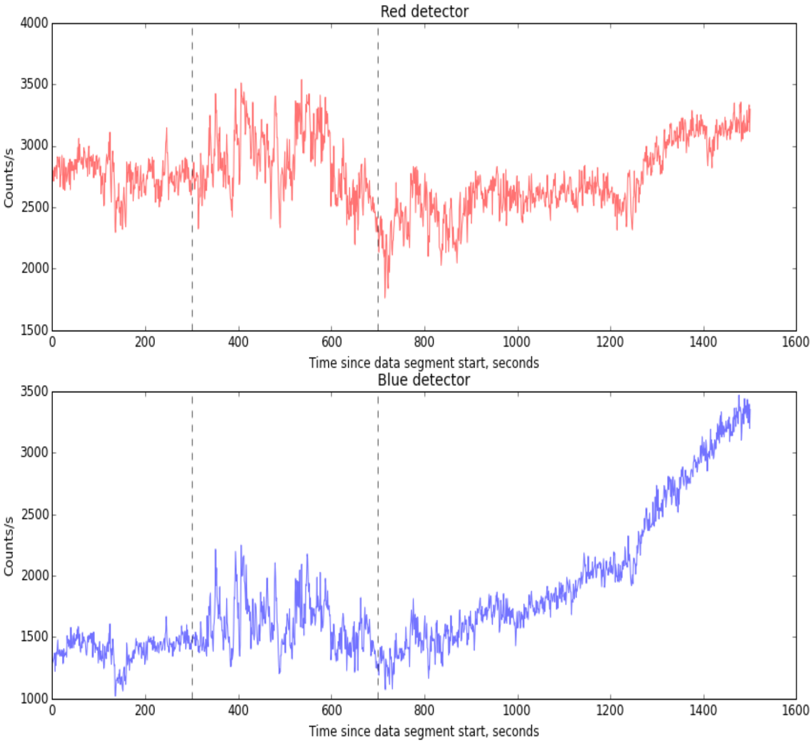

Fig2. *Light curves in the "red" and "blue" channels during the data segment containing coherent optical pulsations on rotational time scale. 400 seconds long time interval when pulsations are evident is marked with vertical dashed lines. Flaring activity is evident during this interval, though such activity is also present on some other data segments lacking signs of coherent pulsations.*

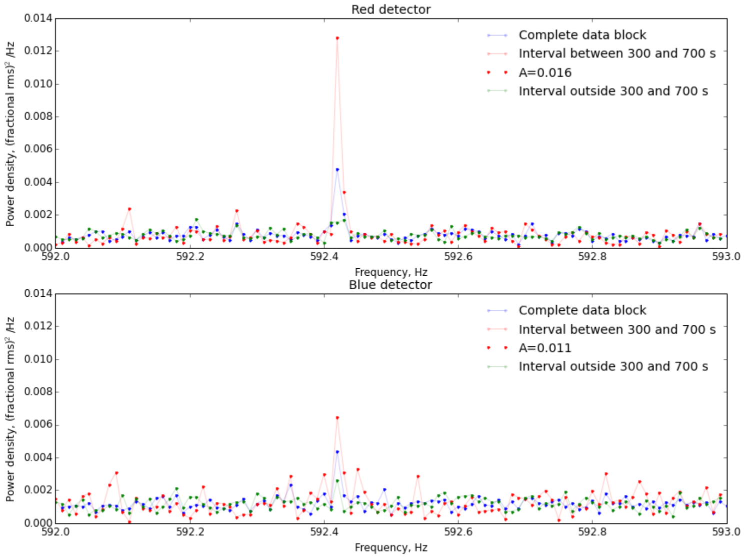

Fig3. *Periodograms of the "red" and "blue" channel light curves of a data segment shown in Figure 2. Shown are the ones for the whole segment (green), inside the activity interval (red) and outside it. The significance of the "red" channel peak inside the 400 seconds long activity interval is better than* 10^{-16} *after correction for the number of trial frequencies. There are no signs for any periodic oscillations outside the activity interval. The amplitudes listed for the peaks correspond to pure sinusoidal variations and are not corrected for the contribution of background emission (see the text for corrected ones).*

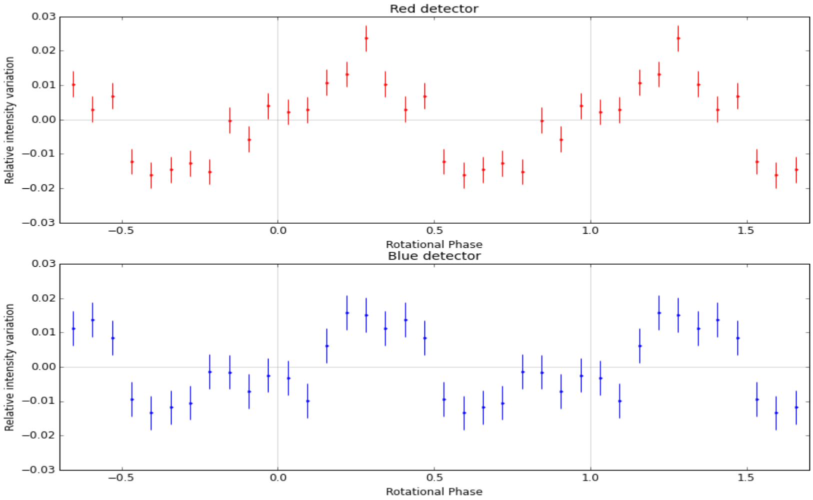

Fig4. *Folded light curves of a 400 seconds long interval containing coherent optical pulsations on rotational frequency in the "red" (upper panel) and "blue" (lower panel) channels. The intensities are not corrected for background text contributions (see the text for corrected amplitudes). The pulse shapes of different channels are similar and co-phased, and are close to sinusoidal shape, with no signs of a two-peaked shape reported by [16],[17],[27].*

3. Discussion and conclusions

In contrast to the results of other studies [16], [17], [27], the folded light curve in our observations tends to have a single-peaked, nearly sinusoidal shape. It is quite similar to the X-ray light curves of isolated radio pulsars, where the pulsations are driven by a relatively uniform thermal emission from polar caps heated by a flow of relativistic particles [28]. However, the estimate for brightness temperature corresponding to the peak fluxes in the pulses of PSR J1023+0038 is $T_{\mathrm{b}} > 10^{11} F_{\nu} D^{2} \nu^{-2} \tau^{-2} \approx 10^{7} - 10^{8}$ K, where F_{ν} is a flux density in Janskys, D is the object distance in kpc, ν is the frequency in units of 10^{15} Hz, and τ is the characteristic time scale of a flux onset in milliseconds. Such large temperatures practically exclude the thermal origin of a pulsed emission, and suggests the non-thermal (synchrotron?) one [29]. On the other hand, [16] and [17] demonstrated that a large, about 10^{31} erg/s, optical pulsed emission can't be explained in neither the scenario of accretion onto neutron star pole, nor as a result of conversion of rotational energy. Finally, [17] suggested the generation of a two-peaked optical and X-ray emission as a result of collision of a pulsar wind with accretion disk, which leads to a shock wave formation and electron acceleration, and, consecutively, to synchrotron emission in a wide range of frequencies due to the motion of accelerated electrons in magnetic fields.

The coherent pulsations we see in our data are significantly different from those reported in [16], [17]. While having approximately the same position inside the binary (according to the time of passage of ascending node) and having comparable amplitudes of 1-2%, our phased light curve has a nearly sinusoidal single-peak shape, and the spectral slope of pulsed component (β~3.7) is much softer than the multi-wavelength slope of $\nu F_{\nu} \sim \nu^{0.3}$ (β=0.7) seen in *high* mode [16] where the optical point was obtained in the white light. The lack of simultaneous X-ray data does not allow estimation of X-ray activity mode during our observations, but the interval of coherent optical pulsations (see Figure 2) is coincident with strong sporadic flaring events on a time scale of seconds to tens of seconds, especially evident in the "blue" band. The latter and a strong time correlation between the optical and X-ray flaring modes found in [16] motivate us to suppose that the system was likely in the *flaring* mode in X-rays as well. This may explain the differences in the spectral slope and the pulse shape. Indeed, the folded X-ray light curve in the *flaring* mode also shows pulsations with a quasi-sinusoidal pulse shape above 3 keV [12]. Albeit marginal (2σ significance), it is remarkably different from the clear double-peaked pulse profile in the high mode while it appears to be similar to what we see in the flaring optical state with much higher significance.

We suggest that the properties of coherent optical emission of PSR J1023+0038 we detected may be explained by synchrotron emission of relativistic electrons moving in a chaotic magnetic field just outside the light cylinder. These particles are accelerated in the current sheets during the reconnections of magnetic field lines in an outflow formed due to interaction of accretion disk with pulsar magnetosphere (the "propeller" regime) [24]. The parameters of this outflow are modulated with rotational period of neutron star, which causes the variations of the synchrotron emission with the same period. We may estimate the parameters of emission region in the following way. For a characteristic frequency of $\nu \sim 5 \cdot 10^{14}$ Hz, synchrotron energy loss timescale shorter than 0.25 of pulsar period, $\tau \sim 0.43$ ms, we get the Lorentz factor $\gamma < 50$ and $B > 1.5 \cdot 10^{5}$ Gauss (which is consistent with magnetic field strength close to the light cylinder). The single electron luminosity is $L \sim 0.1$ erg/s, which, for the pulsed component luminosity of 10^{31} erg/s, gives the number of emitting particles of 10^{32}. As the size of emission region is smaller than $c\tau \sim 10^{7}$ cm, the electron density is $n > 10^{10}$ cm^{-3}.

The results of MHD simulations of accretion/ejection processes onto neutron stars have demonstrated that the process is highly non-stationary, and various parameters – matter density, outflow velocity and inhomogeneity, its luminosity, the structure and strength of magnetic fields – are strongly varying. However, our estimations do not contradict the values of parameters emerging in these simulations. On the other hand, the combination of parameters necessary for generation of coherent optical pulsations may happen sporadically. For example, when the density exceeds some threshold [30], the medium becomes opaque to a synchrotron radiation, and its intensity drops significantly. That may explain why the pulsations are detectable during the *flaring* mode – the chances to get a necessary combination of parameters are higher.

Finally, let's stress the importance of magnetic reconnections for acceleration of electrons that produce the observed optical emission. It seems that only this mechanism may lead to the formation of ensemble of electrons with such soft energetic spectrum, with the slope close to -8 [31] (which is necessary for generation of synchrotron spectrum with the slope of β=3.5).

Finally, our detection of the coherent optical pulsations with characteristics significantly different from those seen in [16], [17], [27] highlights the complex and non-stationary nature of the processes occurring in a binary system containing the transitional millisecond pulsar PSR J1023+0038.

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