
High time resolution multi-band photo-polarimetric observations of the binary millisecond redback pulsar J1023+0038 with the BTA

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Abstract We briefly report first results of high time resolution optical multiband panoramic photo-polarimetric observations of the eclipsing binary millisecond redback pulsar J1023+0038 obtained in February 2017 with the 6 m BTA telescope. Our data show that the pulsar still remained in the low-mass X-ray binary stage, which is characterised by rapid flaring at time scales of 10-100 s with amplitudes of 0.2-0.5 mag. We resolved a fine structure of the flares at time scales of 0.1–10 s. The polarimetry at the time scale of 12 s shows no variable polarization with an upper limit of 2-4% for the linear polarization degree in the flaring and quiet stages. We shortly outline implications of the results.

Keywords: Pulsars: Individual: Psr J1023+0038 — Techniques: Photometric — Techniques: Polarimetric — Accretion

1. Introduction

Rotation powered millisecond pulsars (RMSPs) were discovered in the radio about 35 yr ago, the first one was PSR B1937+21 [1]. Two independent groups immediately suggested that RMSPs were spun-up (“recycled”) by accretion in close binary systems [2, 3]. The mechanism was proposed early [4]. A long time this idea was only supported by the fact that most RMSPs are in binary systems with ordinary stellar companion. The discovery of 401 Hz X-ray coherent pulsations from the accretion powered neutron star (NS) in low mass X-ray binary (LMXB) SAX J1808.4-3658 [5] was the first direct evidence of the accretion spin-up.

Compact RMSPs binaries with binary period $P_b \leq 1$ day show two distinct sub-classes: “black widows” (BWs; [6]) with sub-stellar companion masses $M \leq 0.1M_\odot$ and “redbacks” with $M \geq 0.1M_\odot$ bloated companions close to filling their Roche lobes [7]. The LMXB - RMSP connection was finally firmly established by three recently discovered redbacks: PSR

J1023+0038 [8], XSS J12270-4859 [9, 10], and PSR J1824-2452I [11]. They directly demonstrated transformation from the accretion to the rotation powered MSP stages.

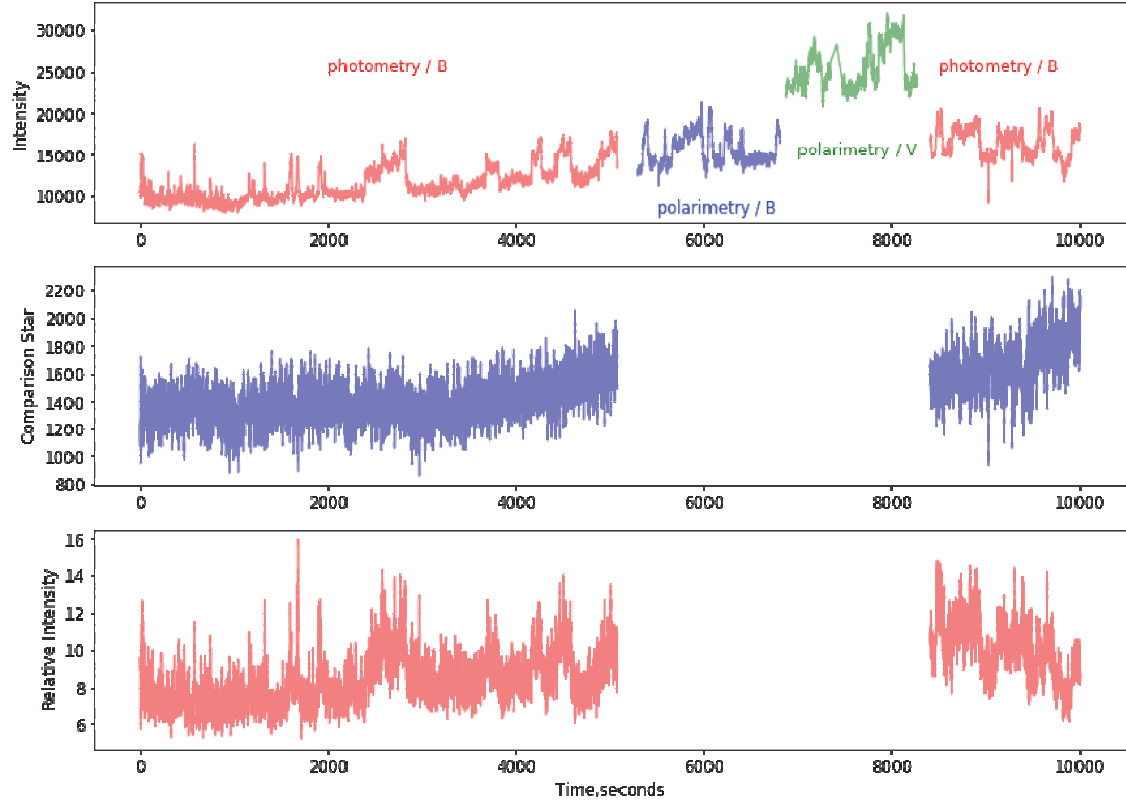


Fig1. Total light curves in counts vs time in seconds from the start of observations of J1023+0038 (top) and the comparison star (middle) in the B band and their ratio (bottom). The data are binned to the bin size of 1.2 s.

Among these three, PSR J1023+0038 is a most studied and intriguing object. It has shown the LMXB to radio RMSP transition in 2003 [8] and then suddenly returned back to a low luminosity accretion stage in 2013 [12]. This demonstrates that the transition itself is a complicated multistage process challenging additional studies. J1023+0038 is an eclipsing binary 1.64 ms pulsar with the 4.754 h orbital period and the $\sim 0.2M_{\odot}$ non-degenerate G-class secondary star. The parallax based distance is 1.37 kpc [13]. Owing to its puzzling behaviour, this object is monitored in different spectral domains from the radio to γ -rays. Its redback nature follows from the modulation of the optical flux and colour with Pb: the pulsar heats the companion's face [14]. The X-ray flux is also modulated with Pb, which is interpreted as the presence of an intro-binary shock. The latter supported by gamma-ray observations [15]. After the transition to the LMBX stage, sporadic switchings between high and low luminosity modes are observed in X-rays on time scales form minutes to hours accompanied by occasional bright flares. Coherent X-ray pulsations with the pulsar period are detected in the high mode, likely due to channeled accretion onto magnetic poles of the NS [16]. It is unusual as compared to typical AMXPs as the implied accretion rate appears to be too low that the accreted matter could overcome the centrifugal barrier of the pulsar. It is also intriguing, that measured spin-down rates in LMBX and RMSP stages is almost the same [17] suggesting that the pulsar wind continues to operate. This is supported by radio brightening detections within the low X-ray mode intervals [18].

In the optical, J1023+0038 is a relatively bright, $V \approx 16.7$, and low reddened, $E(B - V) \approx 0.07$, object. First optical high-time resolution observations with the ULTRACAM in the accretion stage also showed occasional flares and deep dips at a 0.1-1 magnitude level and time scales from 20 s to 10 min [14]. Implied spatial scales of the regions responsible for bright flares can be as small as $0.3R_{\odot}$, which is comparable with accretion disk size. However, many flares and deep fronts are not resolved due to a limited time resolution of about 0.3 s. Higher time resolution observations would be useful to study the variability nature.

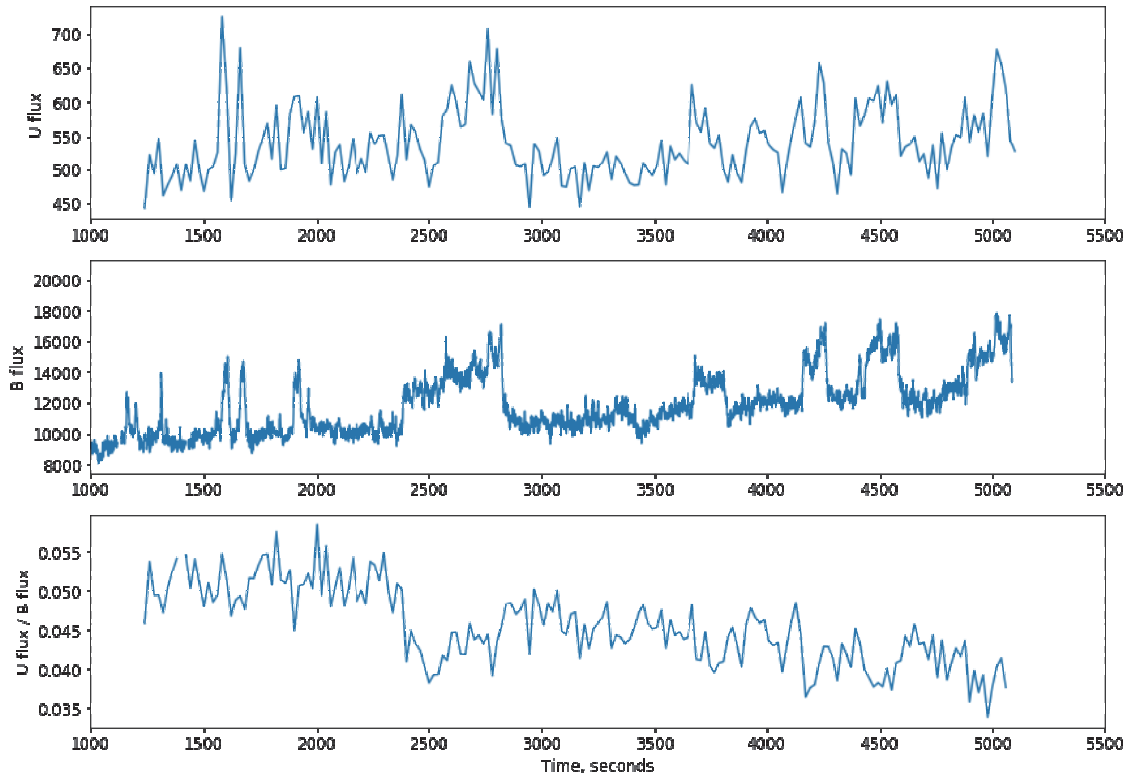


Fig2. Comparison of the U (top) and B (middle) band light curves fragments at bin sizes of 20 and 1.2 s, respectively. Their ratio is shown in the bottom panel.

2. Observations

PSR J1023+0038 was observed in February 17, 2017 during 3.5 h with the Russian 6-m BTA telescope using the Multicolor Panoramic Photo-Polarimeter (MPPP) [19], which is a part of the MANIA experiment [23]. Conditions were clean and seeing was about $1.7''$. The MPPP allows to register photons from the target in four photometric bands and/or to obtain three Stocks parameters simultaneously. Photons can be registered by two detectors: the microchannel plate based position sensitive photon counter (PSD) [24] with multi-alkali photocathode, equipped with the Quantochron 4-48 data acquisition system [25] providing the time resolution up to 100 ns; the low readout noise PhotonMax 512B EMCCD from Princeton Instruments with the resolution up to 1 ms. In our photometric observations we employed both simultaneously in a

“wide-field” regime where the area of 40'' with the target and a comparison star was observed using the EMCCD in the B band with 0.12 s exposures, and using PSD in U band with 1 μ s resolution. Also, a part of time, the polarimetric regime was used when only the target in a square 10'' x 10'' diaphragm was observed in four polarization orientations simultaneously with EMCCD. The latter regime of MPPP is analogous to the one used in [20, 21]. The summary of the observations is listed in **Table1**.

Table1. Summary of observations of PSR J1023+0038 on the Russian 6-m BTA telescope

Start time, UT	End time, UT	Duration, seconds	Detector	Filter	Regime
2017-02-17 18:49:25	2017-02-17 20:14:10	5085	EMCCD	B	photometry
2017-02-17 19:10:06	2017-02-17 20:14:56	3890	PSD	U	photometry
2017-02-17 20:17:33	2017-02-17 20:43:02	1529	EMCCD	B	polarimetry
2017-02-17 20:44:00	2017-02-17 21:07:06	1386	EMCCD	V	polarimetry
2017-02-17 21:09:31	2017-02-17 21:36:07	1596	EMCCD	B	photometry

3. Results

In **Fig1**, the total background subtracted light curve of J1023+0038 in the B band binned to 1.2 s resolution is shown. The data for the stable comparison star and the ratio of the target to this star intensities are presented as well to demonstrate the stability of the instrument performance. The gap in the data correspond to the interval of the polarimetric observations where no comparison star data are available. Several bright flares of different duration are seen in the light curve when the emission intensity sharply increases by a factor of 1.5. Some of them are unresolved at the selected time binning. Unfortunately, in the U band, where we had much higher time resolution, J1023+0038 is much fainter while detector quantum efficiency is lower, and the light curve at the same resolution is much noisier. Nevertheless, main features seen in B are resolved in U, particularly when we use large binning (see **Fig2**). The ratio of U/B shows that during bright episodes J1023+0038 becomes redder, which is consistent with results by Shahbaz et al. [14].

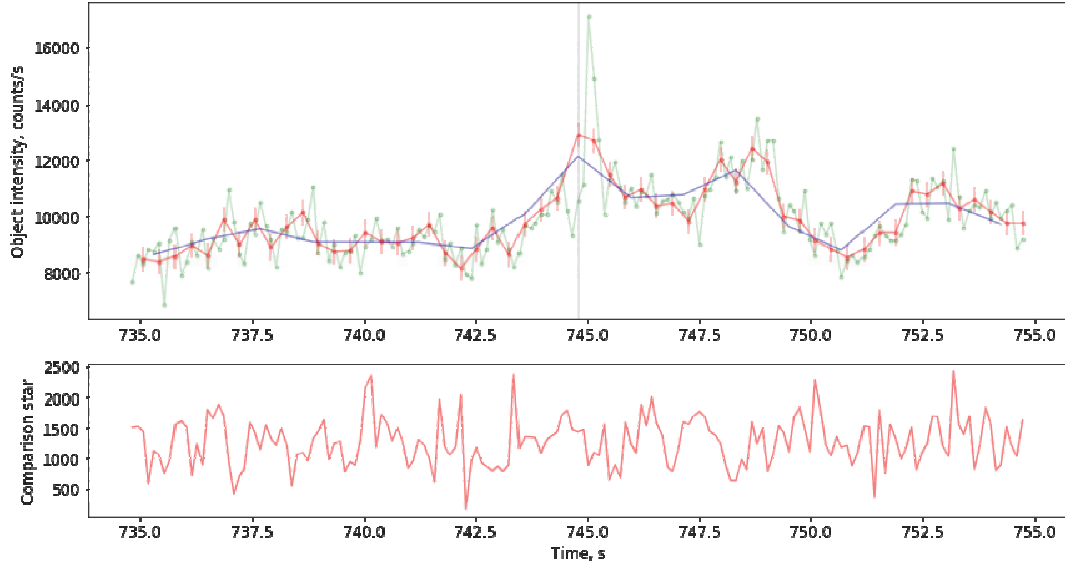


Fig3. Fragment of the B band light curve with a sharp flare. Green, red and blue lines correspond to the native resolution of 0.12 s and binning with 0.4 and 10 s, respectively. The flare disappears with time resolution decrease.

We resolved, for the first time, very sharp bright flares with durations and rising times down to about 0.4 and 0.2 s, respectively. An example is shown in **Fig3.** where we demonstrate also that such flares can hardly be detected at a factor of two-three lower resolution. In some episodes of the observations we see signatures of a periodic flux modulation. Using the Lomb-Scargle periodogram method we found a significant periodicity with the period of 7.6 s and the duration of about 100 seconds in the initial part of the B-band light curve (**Fig4.**). No events of similar significance are seen later.

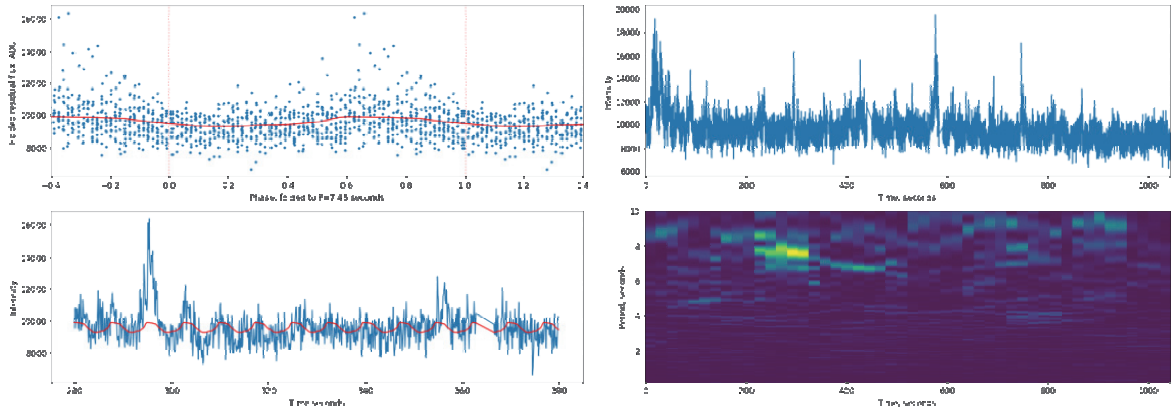


Fig4. Left: initial part of the B band light curve (top) and running Lomb-Scargle periodogram of this curve (bottom) computed using the 100 s window. The peak near $t \sim 300$ s at the periodogram has a significance better than 10^{-6} and probably displays a frequency drift. The best fit period $P=7.6$ s is derived using phase-dispersion minimization (PDM) method. Right: the folded (top) and un-folded (bottom) light curve around the peak. The red line corresponds to the curve derived by smoothing the folded light curve.

The overall light curve (**Fig1.**) seems to demonstrate a transition from a nearly constant and relative low initial (until about 2000 s) intensity level with very short bright spikes towards a stage where sharp sporadic switchings between the low and a bright intensity intervals of

several minutes durations are observed. The latter is reminiscent of the low/high luminosity mode transitions observed in X-rays [18]. This effect definitely needs additional observations in order to properly describe and characterize it.

The Stokes parameters derived at a 12 seconds resolution scale during polarimetric observations are presented in **Fig5**. We find no obvious correlation of the polarization with the intensity variations on the level greater than 2-4% on time scales larger than 12 seconds. Shorter flashes also do not display any polarization greater than 10%.

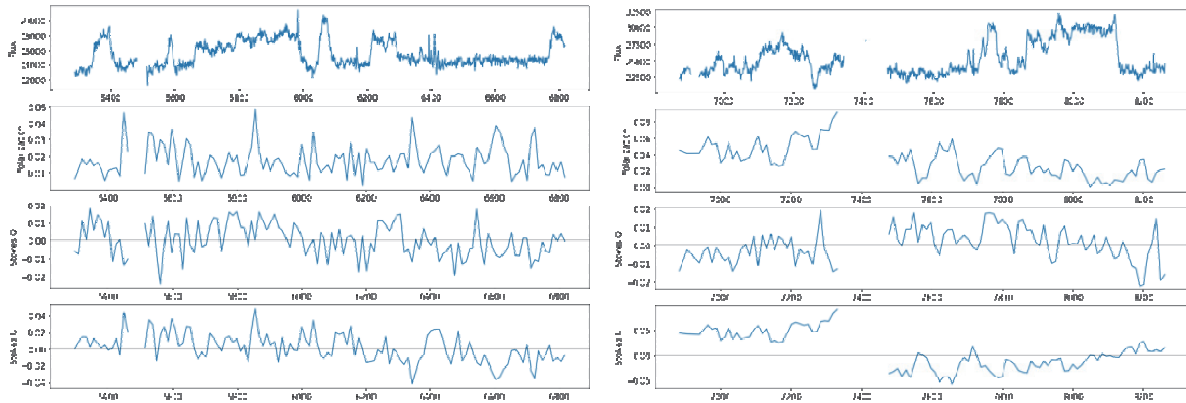


Fig5. From top to bottom: the time variation of the B (left panel) or V (right panel) band flux intensity, the polarization degree, and Stokes parameters Q and U . The time bin is 12 s. Long-term trends in Stokes parameters are due to not fully corrected instrumental polarization depending on the object position on detector. There is no evident correlation of the polarization with large flares in the intensity.

4. Discussion and Conclusions

The temporal resolution of our observations is by a factor of three better as compared with previous observations [14]. This allowed us to resolve, for the first time, the bright flares in the optical emission of J1023+0038 with the durations down to hundred milliseconds. This is in remarkable agreement with predictions of accretion models by Romanova et al. [22] constructed for different propeller regimes. The models suggest a characteristic variability scale in a range of 50–100 ms for the parameters of the J1023+0038 system. Thus, J1023+0038 is likely to be in an unstable propeller regime. We plan to continue observations increasing the time resolution to find the lowest variability scale and to perform detailed comparison with models. Coordinated optical-X-ray-radio high time resolution observations would be very useful to better understand the nature of processes in this remarkable object.

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