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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 multi-band panoramic photo-polarimetric observations of the eclipsing binary millisecond redback pulsar J1023+0038 obtained in February 2017 with the 6 m BTA telescope. The time resolution was varied from 10 to 120 ms depending on observational mode. Our data show that the pulsar still remained in the low-mass X-ray binary stage, 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 0.1 s shows no polarization with an upper limit of 2%–4% for the linear polarisation degree in flaring and quiet stages, while at a 10 minute scale averaging it is about 1.5% at 3σ significance. We shortly outline implications of the results.

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 proposed 6 yr earlier [4]. For a long time this idea was only supported by the fact that most RMSPs are in binary systems with ordinary stellar companions. The discovery of 401 Hz X-ray coherent pulsations from the accretion powered neutron star (NS) in the low mass X-ray binary (LMXB) SAX J1808.4-3658 in 1998 [5] was the first direct evidence of the accretion spin-up.

Compact RMSPs binaries with binary periods $P_b < 1$ day show two distinct sub-classes: “black widows” (BWs; [6]) with sub-stellar companion masses $M < 0.1M_\odot$ and “redbacks” with $M > 0.1M_\odot$ bloated companions close to filling their Roche lobes [7]. The LMXB–RMSP connection was finally firmly established by the recent discovery of three redbacks, PSR J1023+0038 [8], XSS J12270–4859 [9, 10], and PSR J1824–2452I [11], directly showing transformations between the accretion and the RMSP stages. Among these three, PSR J1023+0038 (hereafter J1023) is the most studied and intriguing object. It showed the LMXB–RMSP transition in 2003 [8] and



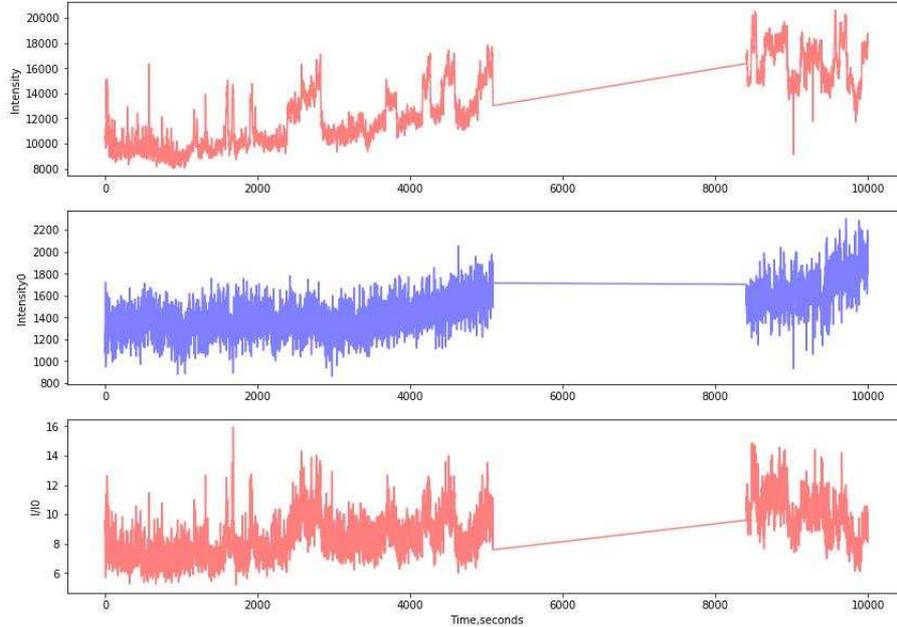


Figure 1. Total light curves in counts per time bin of J1023 (*top*) and the comparison star (*middle*) in the *B* band, and their ratio (*bottom*). The time bin is 1.2 s.

then suddenly returned back to a low-luminosity accretion stage in 2013 [12], demonstrating that the transition itself is a complicated multi-stage process. J1023 is an eclipsing binary 1.64 ms pulsar with the $P_b = 4.754$ h and an $\approx 0.2M_\odot$ non-degenerate G-class companion. The parallax-based distance is 1.37 kpc [13]. The object is being monitored in different spectral domains. Its redback nature follows from the modulation of its optical flux and colour with the period P_b due to heating of the companion’s face by the pulsar [14]. The modulation of the X-ray flux with P_b is interpreted as the presence of an intra-binary shock, which is supported by γ -ray observations [15]. In the accretion stage, J1023 shows sporadic switches between high and low X-ray luminosity modes with durations from minutes to hours, accompanied by occasional bright flares [16]. Coherent X-ray pulsations with the pulsar period, possibly caused by channelled accretion onto magnetic poles of the NS, are detected in the high luminosity mode [17]. However, the implied accretion rate appears to be too low to provide the matter penetration through the centrifugal barrier of the pulsar. It is also intriguing, that the spin-down rates in the LMBX and RMSP stages are almost the same [18], suggesting that the pulsar wind continues to operate. This is supported by the detection of radio brightening episodes during the low X-ray mode intervals [19].

In the optical, J1023 is a relatively bright object, $V \approx 16.7$, with a low extinction, $A_V \approx 0.22$. First optical high time resolution observations in 2015 also showed occasional flares and sharp dips at 0.1–1 magnitude levels and 20 s–10 min time scales [14]. Implied spatial scales can be as small as $0.3R_\odot$, which is comparable with the J1023 accretion disk size. However, many flares and dip fronts were not resolved due to a limited time resolution > 0.3 s. Higher time resolution observations are necessary to study the variability nature.

2. Observations

J1023 was observed on February 17, 2017 during 3.5 h with the 6 m BTA telescope using the Multicolor Panoramic Photo-Polarimeter (MPPP) instrument [20]. Conditions were clean with

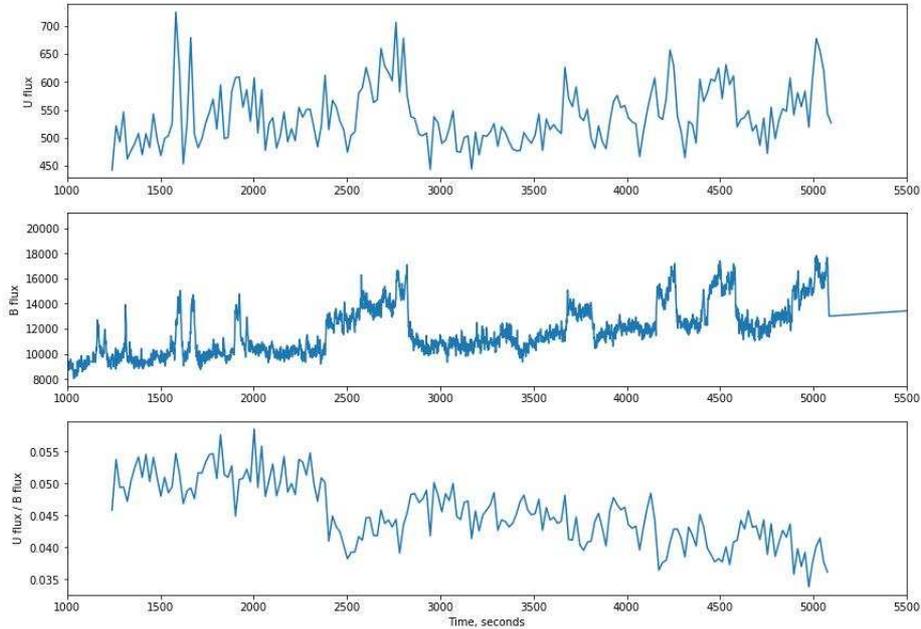


Figure 2. Comparison of the U (*top*) and B (*middle*) band light curve fragments at time bin sizes of 20 and 1.2 s, respectively. The U/B flux ratio is shown in the *bottom* panel.

seeing of $\approx 1''.7$. The MPPP allows one to register photons from the target in four photometric bands and/or to obtain three Stokes parameters simultaneously. Photons can be registered by two detectors: the microchannel-plate-based position-sensitive photon counter (PSD) providing the time resolution up to 100 ns, and the low readout noise PhotonMax 512B EMCCD from Princeton Instruments with the resolution up to 1 ms. In our observations we employed, a “wide-field” regime using the EMCCD, where the area of $40''$ with the target and a comparison star was observed in the B band with 0.12 s exposures, and simultaneous PSD observations with $1 \mu\text{s}$ resolution in the U band. We also used the polarimetric EMCCD mode [21, 22] in B and V bands, in which only the target was observed in four polarization orientations simultaneously.

3. Results

In figure 1, the total background-subtracted light curve of J1023 in the B band binned to 1.2 s resolution is shown. The gap in the data corresponds to the polarimetric observations. The data for a stable comparison star and the intensity ratio of J1023 to the star are presented as well to demonstrate the stability of the instrument performance. Several bright flares of different durations are seen in the light curve of J1023 when the emission intensity sharply increases by a factor of 1.5. Some of them are unresolved at the selected time binning. They are not instrument artifacts as in that case they would also be seen in the star light curve at $(4 - 6)\sigma$ levels. Unfortunately, in the U band, where we had much higher time resolution, J1023 is much fainter and the light curve is much noisier. However, the main features seen in B are also resolved in U , particularly when we apply coarser binning (figure 2). The U/B ratio shows that J1023 becomes redder during bright intervals, which is consistent with the results obtained in [14] in 2015.

We resolved, for the first time, very sharp bright flares with durations and rising times of about 0.3 and 0.1 s, respectively. An example in figure 3 demonstrates that such flares could hardly be detected at a factor of 2–3 lower resolution (red and blue lines). During some short

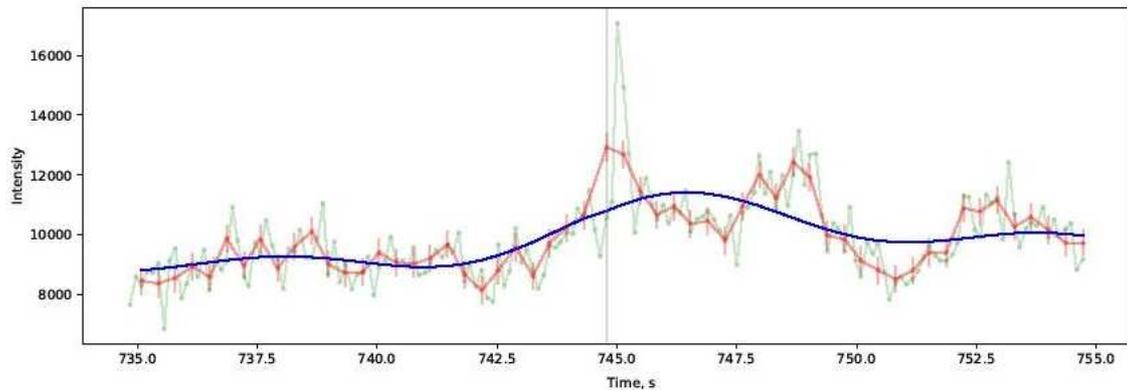


Figure 3. Fragment of the B band light curve with a sharp flare. The green curve is shown at the native resolution of 0.12 s, the red and blue curves are binned to 0.3 and 10 s, respectively.

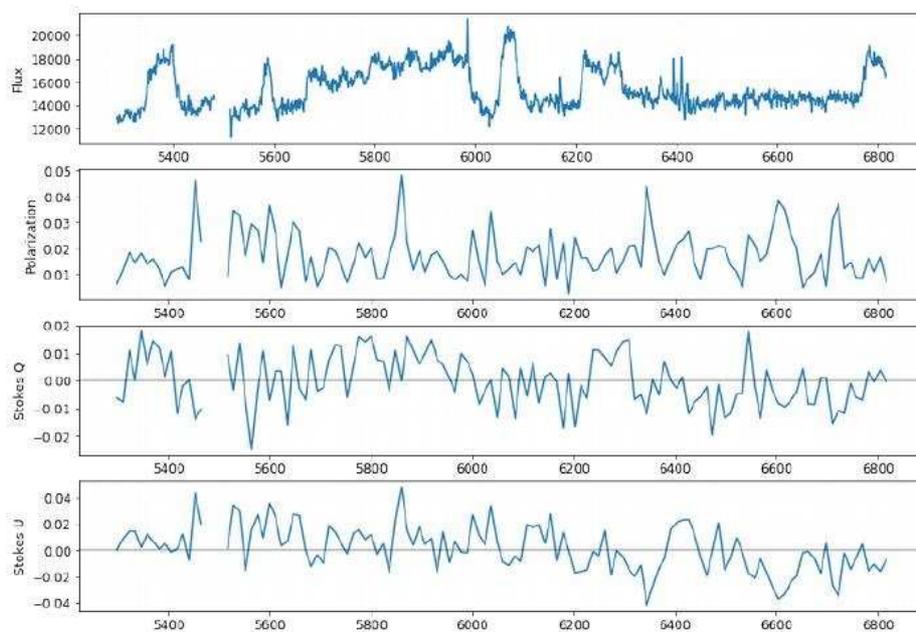


Figure 4. From top to bottom: the B band flux, the polarization degree, and normalised Stokes parameters Q and U of J1023 vs time. The polarisation curves are binned to 12 s.

intervals of ~ 100 s, J1023 showed signatures of a periodic flux modulation. Using the Lomb-Scargle periodogram method, we found a quasi-periodicity with the period of ≈ 7.6 s.

Our polarisation data (figure 4) indicate a linear polarisation degree $p = (1.5 \pm 0.5)\%$ using 10 min averaging. However, this should be considered with caution. No obvious polarisation-intensity correlation is found, and only upper limits $p \leq 2\%$ and 4% can be derived at 10 and 0.1 s resolutions, which are consistent with the radio upper limit of $\approx 4\%$ found in [23].

4. Discussion and Conclusions

Increasing only by a factor of three the time resolution as compared to the previous observations [14] allowed us to resolve, for the first time, bright flares in the optical emission of J1023 with durations of ≈ 100 ms. This implies the presence of bright regions with sizes smaller than the accretion disk and agrees well with the predictions of accretion models for various propeller regimes [24]. For J1023, they suggest a variability scale of 50–100 ms related to an interplay between accretion/outflow episodes. Thus, J1023 is likely to be in an unstable propeller regime. Our polarisation upper limits reject the presence of a bright jet. Optimisation of the MPPP observational setup for J1023 will allow us to better constrain the lowest variability scale and to confirm independently the pulsar optical pulsations recently reported in [25]. Coordinated optical–X-ray–radio high time resolution observations would be very useful in this respect.

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