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Optical monitoring of a transitional millisecond pulsar: PSR J1023+0038

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Abstract. PSR J10203+0038 is a transitional millisecond pulsar (tMSP) in an eclipsing binary system, which has been observed to switch between the radio loud millisecond pulsar (MSP) and low-mass-X-ray binary (LMXB) states. This behavior offers a great opportunity to study the origin of MSPs and confirming the 'recycling' scenario, a theoretical model of MSP's origin. We develop an automated pipeline to monitor the system using Python programming language and Source-Extractor software for detecting the objects and measuring its magnitude. We obtain a series of observations with the 0.6m PROMPT-8 telescope at Cerro Tololo in Chile. The magnitude threshold for alert has been set 16.884 mag in R filter. When the magnitude of the system increases over the limit, 16.884 mag in filter R, the pipeline will alert us about the next possible switching of this system. The pipeline has been running on server at National Astronomical Research of Thailand (NARIT) since January 2018. We have found that, during January and February 2018, the system still remains in LMXB state.

1. Introduction

A millisecond pulsar (MSP)'s formation scenario was proposed by Alpar et al.(1982) [1], that they are formed in an X-ray binary system where the neutron star was gaining additional angular momentum and spun-up via mass accretion process from its companion star. As a result, these MSPs or 'recycled' pulsars have spin periods in milliseconds domain, which is much faster than normal pulsars. PSR J1023+0038 and its companion was originally reported as a radio cataclysmic variable, FIRST J102347.6+003841 [2]. The V magnitude of the system was observed to be $\sim$17.5, where $\sim$1 magnitude flares also detected. There is also an indication of an accretion disk from the observed double-peaked emission. Subsequently, the system was shown to be a Low Mass X-ray Binary (LMXB) system [3] . Later in 2013, along with the disappearance of the accretion disk, PSR J1023+0038 was discovered as an radio MSP with a spin period of 1.69 ms as part of a 350-MHz pulsar survey with the Green Bank Telescope, and identified to be in the same system [4]. Stappers et al.(2014) [5] reported that during the last two weeks in July, 2014, the radio pulsation has disappeared and γ-ray flux density increases significantly by a factor of 5. The optical, UV and X-ray observations confirmed the formation of an accretion disk in this system. Halpern et al. (2013) reported an decrease in V magnitude from ∼17.5 to ∼16.5 [6]. The system remains in the LMXB state. Multi-wavelength information prior and after the switch of the system therefore allows astronomers to gain a better insight in the nature of accretion process in LMXB as well as the evolution of MSPs. And if the MSP formation scenario is correct, in the future once the mass transfer is prohibited, the system is expected to change into the MSP state again. The flowchart of the monitoring pipeline is presented in Section 2. The observed lightcurves , the distribution of the magnitude and detection strategy are discussed in Section 3.

2. Monitoring and Data Analysis

The pipeline was designed to work with *Skynet* Robotic Network System[1] for the 0.6m PROMPT-8 telescope [7], and subsequently with the Thai Robotic Telescope Network[2]. The monitoring script, figure 1, begins with an if-condition where an un-processed observations is downloaded from *Skynet* or adding 10 minutes delay and start again. The downloaded image is then process with *SExtractor* [8] to produce a list of position and magnitude of all objects in the image. The second if-condition is to locate the target, PSR J1023+0038, where no detection immediately triggers the alert routine. For detection case, if the magnitude value is below the limit, an alert will be triggered as well. If not, the script will continue to the next do exists e is the observation table, which has been submitted to *Skynet* system. Upon triggered, an email containing the magnitude value will be sent to a list of recipients.

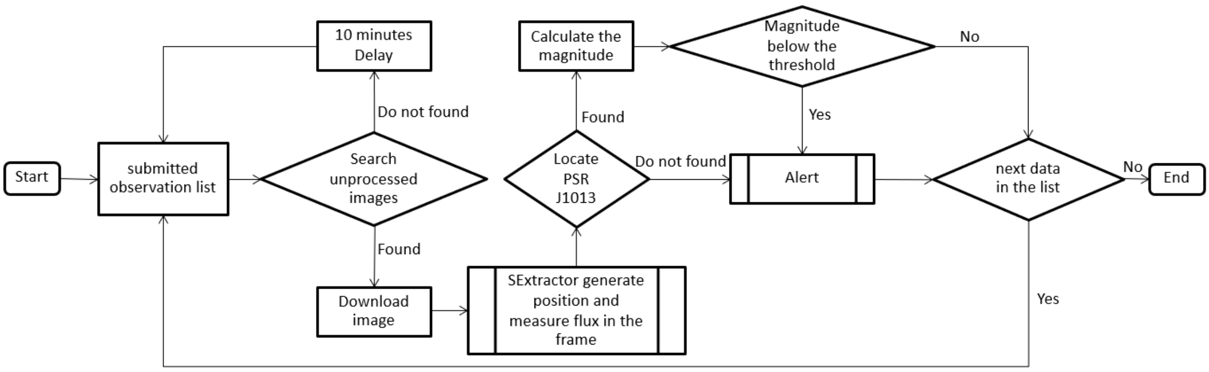

Figure 1. The flowchart of the monitoring pipeline.

3. Results and Discussion

Between January and February 2018, we obtained photometric data observed with the 0.6 PROMPT-8 in R filter with 60-s exposure time. An example of the observed 4.8-hr lightcurve is presented in figure 2, which indicates 0.4 magnitude from the orbit. The PROMPT-8 data presented here are used for determining the optimised magnitude threshold for the alert. A distribution of the measured magnitude of the total of 985 frames is shown in figure 3. It appears to consist of the normally distributed center population and a subtle component at ∼15.6 to ∼16.0 magnitude, which arises from the optical burst activity of the system previously reported [9][10]. The burst corresponds to the additional 0.3 magnitude frame-to-frame variations in figure 2. Due to the deviation from guassian, we calculate the statistics of the distribution from both standard deviation error and median-percentile. We obtain the mean value (μ) of 16.274

[1] www.skynet.unc.edu
[2] www.narit.or.th

and the median value (M) of 16.296. The 1-σ, 2-σ and 3-σ confidence limits are shown in table 1 and indicated by arrows in figure 3. Comparing to the standard error method, the limits calculated from the median-percentile method, which corresponds to the 68.27-percentile (1-σ), 95.45-percentile (2-σ) and 99.73-percentile (3-σ) of the data, are more robust in representing the distribution. The upper 1-2-3-σ and the lower 1-σ values are more concentrated to the center, while the lower 2-3-σ is scattered further corresponding to the small population of the burst component. The optimal threshold value can be between two compromises; 1) if the value is too high, it would take longer to detect the changes; 2) if the value is too low, there will be to many false alarm. For the first stage of the monitoring, the trigger threshold is set to the highest observed magnitude 16.884.

The uncertainty in the transition window depends on the monitoring cadence, the orbital phase observed and how quickly the magnitude increases compared with the 0.4 magnitude orbital variation. The 0.3 magnitude frame-to-frame variation is not included as the burst only decreases value. Because there is no information on the switching timescale from the first transition to the MSP state occurred prior 2013, assuming that the LMXB-to-MSP transition takes 2 weeks and the magnitude difference is 1, similar to the MSP-to-LMXB switch in July, 2014 [5] [6], we obtain the rate of magnitude increase of $1/14 = 0.07$ per day. Therefore, for worse case when the monitoring occurs at the bright orbital phase, the current monitoring setup can take up to 5.7 days for detecting the transition. For future work, this value can be improved by taking into account the orbital ephemeris where the remaining uncertainty is due to measurement uncertainty.

Table 1. The calculated confidence limits at 68.27%, 95.45% and 99.73% from the standard deviation (μ) and median-percentile (M) methods. The values are also indicated as arrows in figure 2.

Confidence limit	lower (μ)	upper (μ)	lower (M)	upper (M)
68.27% (1-σ)	16.052	16.496	16.193	16.385
95.45% (2-σ)	15.830	16.718	15.838	16.606
99.73% (3-σ)	15.608	16.941	15.568	16.830

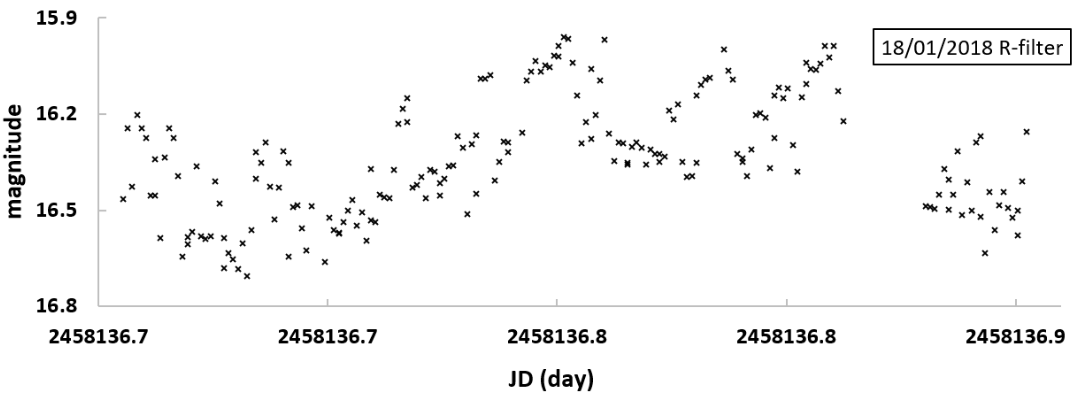

Figure 2. The lightcurve of the 4.8-hr PROMPT-8 observation on 18 January, 2018.

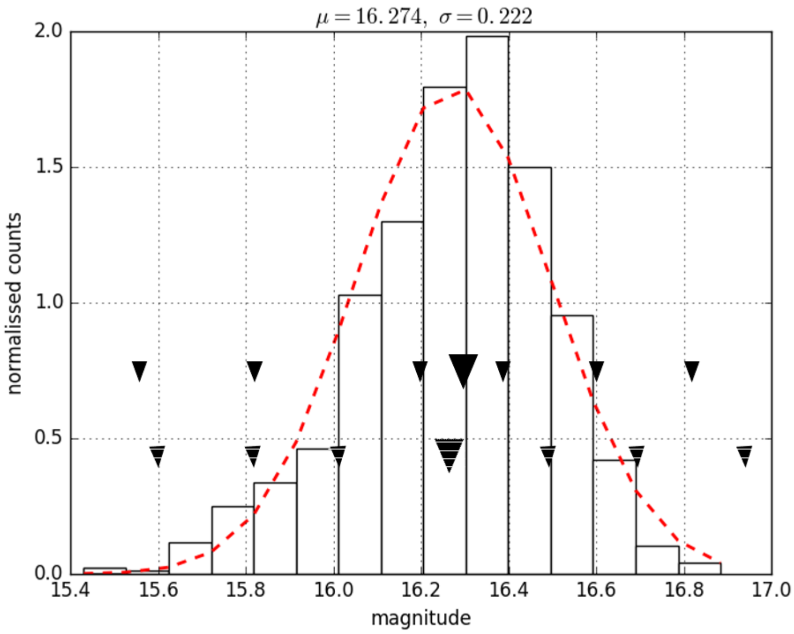

Figure 3. The distribution of the magnitude of the dataset. The red line indicates the best fit of a gaussian function. The arrows on the lower and upper rows represent the statistics calculated from the standard deviation error and the median-percentile methods, respectively.

4. Conclusions

We have developed an automated software routine for the optical monitoring campaign of PSR J1023+0038 with PROMPT-8 telescope, where worse-case scenario for detecting transition window is 5.7 days. This value can be improved in future work by taking into account the orbital phase of the system.

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