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The study of coherent optical pulsations of the millisecond pulsar PSR J1023+0038 on Russian 6-m telescope

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Abstract
We observed the millisecond redback pulsar PSR J1023+0038 in its accreting regime on two nights in November 2017 on Russian 6-m telescope with a high-temporal resolution panoramic photometer-polarimeter in a two-channel ("blue" and "red") setup. During 400 s (12% of nearly 3 hr 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 the radio data, with amplitudes of 2.1% ("red") and 1.3% ("blue"). Corresponding luminosity of pulsed component is about 10^{31} erg s^{-1} 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.

KEYWORD
stars: neutron; pulsars: individual (PSR J1023+0038); accretion, accretion disks; techniques: photometric

1 | INTRODUCTION

The first millisecond radio pulsar, PSR B1937 + 21, was discovered in 1982 (Backer et al. 1982), and its nature was immediately explained in view of the concept of neutron star rotation speedup during the accretion of matter from a companion star in a compact binary system (Alpar et al. 1982). 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 (Bisnovatyi-Kogan & Komberg 1974). Finally, three systems were found to contain a neutron star transitioning from accretion to ejection stages—PSR J1023+0038 (Archibald et al. 2009), XSS J12270-4859 (Bassa et al. 2014), and PSR J1824-2452I (Papitto et al. 2013). The most interesting 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 (Bond et al. 2002). To date, it was twice observed switching the stage—from accretion to ejection in 2003 (Archibald et al. 2009) and back to accretion in 2013 (Stappers et al. 2014). This object is a "redback" compact binary with 4.75-hr period, containing a 0.2 $M_\odot$ G class normal component overflowing its Roche lobe, at a 1.37 kpc distance from Earth (Deller et al. 2012). 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 (Takata et al. 2014). Moreover, the X-ray emission was found to consist of three separate states—high ($7 \cdot 10^{33}$ erg s^{-1}), low (10^{33} erg s^{-1}), and flaring (10^{34} erg s^{-1}) with intensity variations on tens of seconds time scale, with state switching

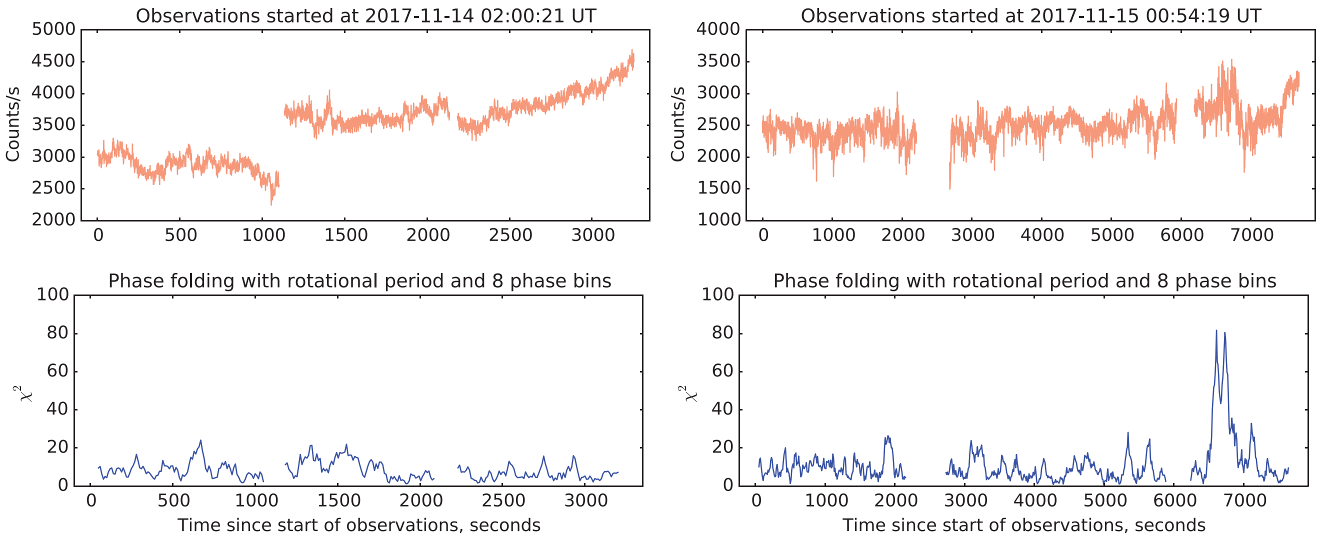

FIGURE 1 Overall light curves for a data from "red" detector (up) and phase-folding χ^2 (down) using Jaodand et al. (2016) timing solution in 100 s wide sliding windows. Left panel—data from night on November 13, 2017. Right panel—data from next night, November 14, 2017. Gaps separate continuous intervals of observations (data segments). Telescope pointing was adjusted between these observations, which explain the intensity jumps between segments. Only single 400 s long interval in the last data segment contains significant pulsations on neutron star rotational period

occurring rapidly and sporadically (Bogdanov et al. 2015; Campana et al. 2016; Coti Zelati et al. 2018; Patruno et al. 2014). Coherent X-ray pulsations with a neutron star rotational period of 1.69 ms are detectable only in high state (Archibald et al. 2015; Papitto et al. 2019), in contrast to the optical ones, which were detected in flaring state too (Ambrosino et al. 2017; Papitto et al. 2019). In optical and infrared bands, PSR J1023+0038 also displays sporadic activity on time scales of seconds to hours (Hakala & Kajava 2018; Kennedy et al. 2018; Shahbaz et al. 2015; Shahbaz et al. 2018). The minimal variability time scale of optical emission is as fast as fractions of seconds (Beskin et al. 2018; Shibanov et al. 2017), which is close to the characteristic time scales of variability due to matter fragmentation in the propeller regime in magneto-hydordinamical (MHD) simulations (Romanova et al. 2018). The discovery of coherent optical pulsations synchronous with that of X-ray and having a characteristic double sinusoidal pulse shape during an accretion stage was an extremely important and unexpected result (Ambrosino et al. 2017; Papitto et al. 2019). It was suggested that these multiwavelength pulsations may be caused by a synchrotron emission of electrons in the region of collision of pulsar wind with accretion flow (Papitto et al. 2019).

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 on Russian 6-m telescope in November 2017, and discuss its nature.

2 | OBSERVATIONS AND RESULTS

We observed millisecond pulsar PSR J1023+0038, which is currently in the accretion stage, on November 14 and 15, 2017, on Russian 6-m telescope using panoramic photometer-polarimeter in the dual-channel regime, using two microchannel plate-based panoramic photon counters ("red" with GaAs photocathode on 5640 Å effective wavelength and "blue" with multialcali photocathode on 4530 Å effective wavelength) to detect and register all photons in a $10'' \times 10''$ diaphragm around the object (Plokhotnichenko et al. 2009). The total duration of observations was about 3 hr (1 hr on first night; 2 hr second night); effective temporal resolution was 1 ¯s. 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 of Jaodand et al. (2016), adjusting the epoch of ascending node by 25.6 s by maximizing the phase-folding χ^2 analogous to the method used by Papitto et al. (2019) and Zampieri et al. (2019).

Time-resolved spectral analysis of the corrected data revealed a single 400-s long interval with significant (peak significance is better than 10^{-16}) oscillations present around rotational frequency of a neutron star. All other data intervals lack any peak there. Time-resolved phase folding using timing solution from Jaodand et al. (2016) also revealed single-pulsed activity interval only (Figures 1–3). Figure 4 shows the phase-folded light curves in both color bands over this time interval, produced using the ephemerides from Jaodand et al. (2016).[1] The shape of folded light curves is nearly sinusoidal, in contrast to two peaks seen by Ambrosino et al. (2017), Papitto et al. (2019), and Zampieri

[1]Unfortunately, the interval of pulsed activity in our data is too short to derive an independent timing solution beyond the adjustment of the epoch of ascending node.

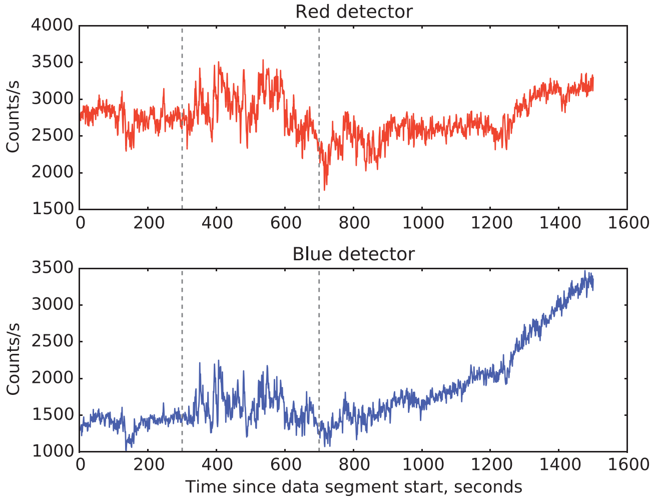

FIGURE 2 Light curves in "red" and "blue" channels during the data segment containing coherent optical pulsations on rotational time scale. A total of 400 s long time interval when pulsations are evident is marked with vertical dashed lines. Flaring activity is evident during this interval, though such activity is also present on some other data segments lacking signs of coherent pulsations

et al. (2019). Amplitudes of the pulsations after correction for the background flux contribution are $A_R = 2.1\%$ in "red" channel and $A_B = 1.3\%$ in "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 (Papitto et al. 2019) and the throughput curves of channels, corresponds to absolute fluxes $F_B = 16 \pm 3$ and $F_B = 6.8 \pm 2.5$ microJansky. Therefore, for a distance to the object of 1.37 kpc (Deller et al. 2012), the optical luminosity of pulsed component is about 10^{31} erg s^{-1} with an accuracy of about 30%. Assuming the power law spectrum $F_\nu \propto \nu^{-\beta}$ for a pulsed component, its slope is $\beta = 3.8$ (2.1–5.9 for 95% confidence interval).

3 | DISCUSSION AND CONCLUSIONS

In contrast to the results of other studies (Ambrosino et al. 2017; Papitto et al. 2019; Zampieri et al. 2019), the folded light curve in our observations tends to have a single peak, 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 (Zavlin 2007). However, the estimate for a brightness temperature corresponding to the peak fluxes in the pulses of PSR J1023+0038 is $T_b > 10^{11} F_\nu D^2 \nu^{-2} \tau^{-2} \approx 10^7 - 10^8$ 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 ms. Such large temperatures practically exclude the thermal origin of a pulsed emission and suggest the nonthermal (probably synchrotron) (Dulk 1987). On the other hand, Papitto et al. (2019) and Ambrosino et al.

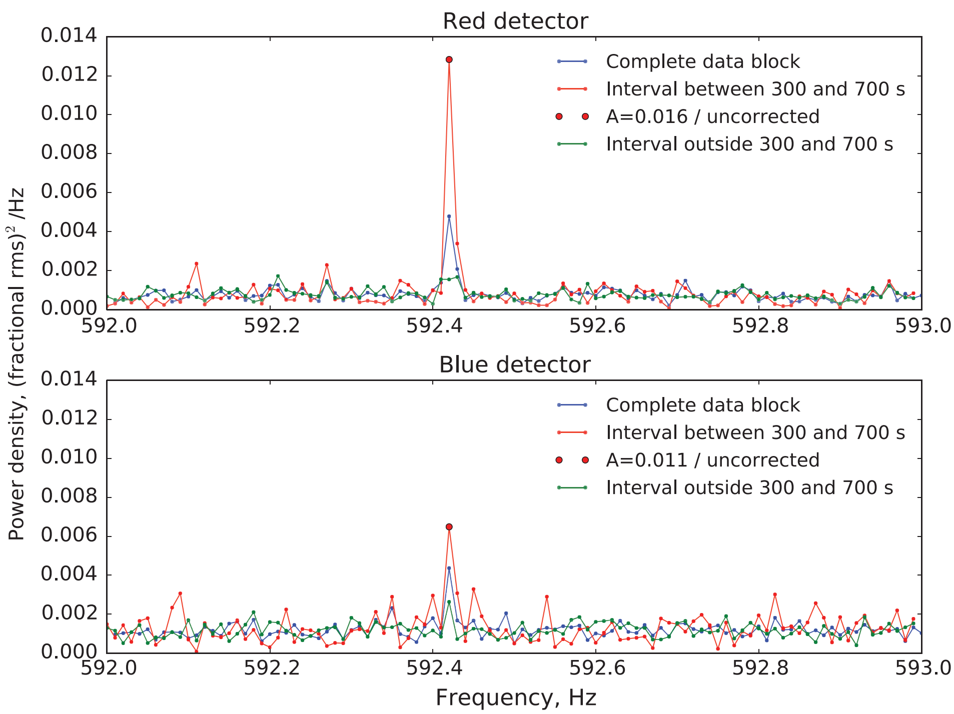

FIGURE 3 Periodograms of the "red" and "blue" channel light curves of a data segment shown in Figure 2. Shown are the ones for the whole segment (green), inside the activity interval (red) and outside it. The significance of the "red" channel peak inside the 400 s long activity interval is better than 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)

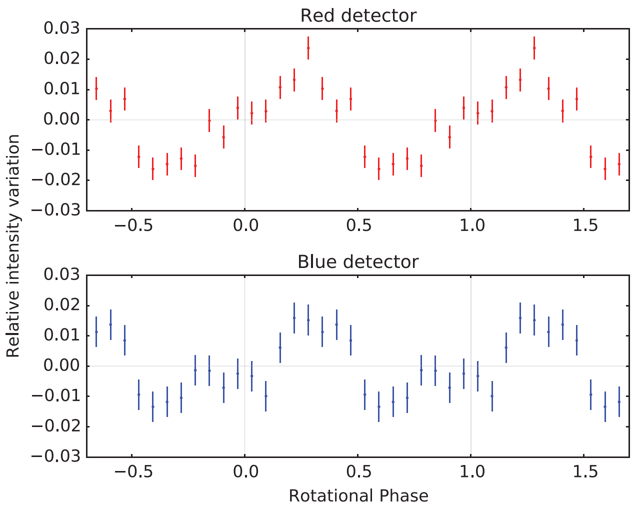

FIGURE 4 Folded light curves of a 400 s long interval containing coherent optical pulsations on rotational frequency in "red" (upper panel) and "blue" (lower panel) channels. The intensities are not corrected for background light contributions (see the text for corrected amplitudes). The pulse shapes of different channels are similar and cophased, and are close to sinusoidal shape, with no signs of a two-peaked shape reported by Ambrosino et al. (2017), Papitto et al. (2019), and Zampieri et al. (2019)

(2017) demonstrated that a large, about 10^{31} erg s^{-1}, optical pulsed emission cannot be explained in neither the scenario of an accretion onto neutron star pole nor as a result of conversion of rotational energy. Finally, Ambrosino et al. (2017) 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 the 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 the ones reported by Papitto et al. (2019) and Ambrosino et al. (2017). 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 ($\beta = 3.1$) is much softer than multi-wavelength slope of $\nu F_\nu \sim \nu^{0.3}$ seen in high mode (Papitto et al. 2019). 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 (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 may tentatively suggest that the system was in flaring mode, which may explain the differences in the spectral slope and probably pulse shape. Indeed, the folded X-ray light curve during a flaring mode also shows a (marginal, with 2σ significance only) signature of pulsations with quasi-sinusoidal shape (Bogdanov et al. 2015).

We suggest that the properties of the coherent optical emission of PSR J1023+0038 we detected may be explained by a 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 ("propeller" regime) (Romanova et al. 2018). The parameters of this outflow are being 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 time scale shorter than 0.25 of pulsar period, $\tau \sim 0.43$ ms, we get $\gamma < 50$ and $B > 1.5 \cdot 10^5$ Gauss (which is consistent with magnetic field strength close to light cylinder). Single electron luminosity is $L \sim 0.1$ erg s^{-1}, which, for the pulsed component luminosity of 10^{31} erg s^{-1}, 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 nonstationary, and various parameters—matter density, outflow velocity and inhomogeneity, its luminosity, and 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 a generation of coherent optical pulsations may happen sporadically. For example, when the density exceeds some threshold (Rybicki & Lightman 1979), the medium becomes opaque to a synchrotron radiation, and its intensity drops significantly. This may explain why the pulsations are detectable during the flaring mode—the chances to get a necessary combination of parameters are higher.

Finally, let us stress the importance of magnetic reconnections for an 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 −8.6 (Oka et al. 2018) (which is necessary for generation of synchrotron spectrum with the slope of $\beta = 3.8$).

Finally, our detection of the coherent optical pulsations with characteristics significantly different from the ones seen in Ambrosino et al. (2017), Papitto et al. (2019), and Zampieri et al. (2019) highlights the complex and nonstationary nature of the processes occurring in a binary system containing transitional millisecond pulsar PSR J1023+0038.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

S.K. participated in observations and performed all data analysis. G.M. participated in observations and led the discussion in the manuscript. V.P. created and operated the instrumentation used and also participated in observations. Yu.S. and D.Z. participated in the discussion of results.

REFERENCES

Alpar, M. A., Cheng, A. F., Ruderman, M. A., & Shaham, J. 1982, *Nature*, *300*, 728.

Ambrosino, F., Papitto, A., Stella, L., Meddi, F., Cretaro, P., Burderi, L., Di Salvo, T., Israel, G.L., Ghedina, A., Di Fabrizio, L., Riverol, L. 2017, *Nat. Astron.*, *1*, 854.

Archibald, A. M., Stairs, I. H., Ransom, S. M., Kaspi, V.M., Kondratiev, V.I., Lorimer, D.R., McLaughlin, M.A., Boyles, J., Hessels, J.W.T., Lynch, R., van Leeuwen, J., Roberts, M.S.E., Jenet, F., Champion, D.J., Rosen, R., Barlow, B.N., Dunlap, B.H., Remillard, R.A. 2009, *Science*, *324*, 1411.

Archibald, A. M., Bogdanov, S., Patruno, A., Hessels, J.W.T., Deller, A.T., Bassa, C., Janssen, G.H., Kaspi, V.M., Lyne, A.G., Stappers, B.W., Tendulkar, S.P., D'Angelo, C.R., Wijnands, R. 2015, *ApJ*, *807*, 62.

Backer, D. C., Kulkarni, S. R., Heiles, C., Davis, M. M., & Goss, W. M. 1982, *Nature*, *300*, 615.

Bassa, C. G., Patruno, A., Hessels, J. W. T., Keane, E.F., Monard, B., Mahony, E.K., Bogdanov, S., Corbel, S., Edwards, P.G., Archibald, A.M., Janssen, G.H., Stappers, B.W., Tendulkar, S. 2014, *MNRAS*, *441*, 1825.

Beskin, G., Karpov, S., Plokhotnichenko, V. L. Shibanov, Yu.A., Zyuzin, D.A., Kholtygin, A.F., Sokolov, V.V. Baryshev, Yu.V. 2018, in: High time resolution multi-band photo-polarimetric observations of the binary millisecond redback pulsar J1023+0038 with the BTA. Proceedings of The International Conference IJSN 1987A, Quark Phase Transition in Compact Objects and Multimessenger Astronomy, Russia, Terskol (BNO INR RAS), Nizhnij Arkhyz (SAO RAS), 2-8 July 2017, INR RAS, Moscow, 24–31.

Bisnovatyi-Kogan, G. S., & Komberg, B. V. 1974, *SvA*, *18*, 217.

Bogdanov, S., Archibald, A. M., Bassa, C., Hessels, J.W.T., Janssen, G.H., Lyne, A.G., Moldon, J., Paragi, Z., Patruno, A., Perera, B.B.P., Stappers, B.W., Tendulkar, S.P., D'Angelo, C.R., Wijnands, R. 2015, *ApJ*, *806*, 148.

Bond, H. E., White, R. L., Becker, R. H., & O'Brien, M. S. 2002, *PASP*, *114*, 1359.

Campana, S., Coti Zelati, F., Papitto, A., Rea, N., Torres, D. F., Baglio, M. C., & D'Avanzo, P. 2016, *A&A*, *594*, A31.

Coti Zelati, F., Campana, S., Braito, V., Baglio, M. C., D'Avanzo, P., Rea, N., & Torres, D. F. 2018, *A&A*, *611*, A14.

Deller, A. T., Archibald, A. M., Brisken, W. F., Chatterjee, S., Janssen, G.H., Kaspi, V.M., Lorimer, D., Lyne, A.G., McLaughlin, M.A., Ransom, S., Stairs, I.H., Stappers, B. 2012, *ApJ*, *756*, L25.

Dulk, G. A. 1987, in: *Cool Stars, Stellar Systems, and the Sun*, eds. J. L. Linsky & R. E. Stencel, Springer Berlin Heidelberg (Berlin, Heidelberg), 72.

Hakala, P., & Kajava, J. J. E. 2018, *MNRAS*, *474*, 3297.

Jaodand, A., Archibald, A. M., Hessels, J. W. T., Bogdanov, S., D'Angelo, C.R., Patruno, A., Bassa, C., Deller, A.T. 2016, *ApJ*, *830*, 122.

Kennedy, M. R., Clark, C. J., Voisin, G., & Breton, R. P. 2018, *MNRAS*, *477*, 1120.

Oka, M., Birn, J., Battaglia, M.,Chaston, C.C., Hatch, S.M., Livadiotis, G., Imada, S., Miyoshi, Y., Kuhar, M., Effenberger, F., Eriksson, E., Khotyaintsev, Y.V., Retino, A. 2018, *Space Sci. Rev.*, *214*, 82.

Papitto, A., Ferrigno, C., Bozzo, E., Rea, N., Pavan, L., Burderi, L., Burgay, M., Campana, S., di Salvo, T., Falanga, M., Filipovic, M.D., Freire, P.C.C., Hessels, J.W.T., Possenti, A., Ransom, S.M., Riggio, A., Romano, P., Sarkissian, J.M., Stairs, I.H., Stella, L., Torres, D.F., Wieringa, M.H., Wong, G.F. 2013, *Nature*, *501*, 517.

Papitto, A., Ambrosino, F., Stella, L., Torres, D.F., Coti Zelati, F., Ghedina, A., Meddi, F., Sanna, A., Casella, P., Dallilar, Y., Eikenberry, S., Israel, G.L., Onori, F., Piranomonte, S., Bozzo, E., Burderi, L., Campana, S., de Martino, D., Di Salvo, T., Ferrigno, C., Rea, N., Riggio, A., Zampieri, L. 2019, *arXiv e-prints*, *1904*, 10433.

Patruno, A., Archibald, A. M., Hessels, J. W. T., Bogdanov, S., Stappers, B.W., Bassa, C.G., Janssen, G.H., Kaspi, V.M., Tendulkar, S., Lyne, A.G. 2014, *ApJ*, *781*, L3.

Plokhotnichenko, V. L., Beskin, G. M., de Bur, V. G., Karpov, S.V., Badjin, D.A., Lyubetskaya, Z.V., Lyubetskij, A.P., Pavlova, V.V. 2009, *Astrophys. Bull.*, *64*, 308.

Romanova, M. M., Blinova, A. A., Ustyugova, G. V., Koldoba, A. V., & Lovelace, R. V. E. 2018, *New Astron.*, *62*, 94.

Rybicki, G. B., & Lightman, A. P. 1979, *Radiative Processes in Astrophysics*, Wiley-Interscience (New York).

Shahbaz, T., Linares, M., Nevado, S. P., Rodriguez-Gil, P., Casares, J., Dhillon, V.S., Marsh, T.R., Littlefair, S., Leckngam, A., Poshyachinda, S. 2015, *MNRAS*, *453*, 3461.

Shahbaz, T., Dallilar, Y., Garner, A., Eikenberry, S., Veledina, A., & Gandhi, P. 2018, *MNRAS*, *477*, 566.

Shibanov, Y. A., Beskin, G. M., Karpov, S. V., Plokhotnichenko, V.L., Zyuzin, D.A., Kholtygin, A.F., Sokolov, V.V. Baryshev, Yu.V. 2017, *J. Phys.: Conf. Ser.*, *932*, 012027.

Stappers, B. W., Archibald, A. M., Hessels, J. W. T., Bassa, C.G., Bogdanov, S., Janssen, G.H., Kaspi, V.M., Lyne, A.G., Patruno, A., Tendulkar, S., Hill, A.B., Glanzman, T. 2014, *ApJ*, *790*, 39.

Takata, J., Li, K. L., Leung, G. C. K., Kong, A.K.H., Tam, P.H.T., Hui, C.Y., Wu, E.M.H., Xing, Y., Cao, Y., Tang, S., Wang, Z., Cheng, K.S. 2014, *ApJ*, *785*, 131.

Zampieri, L., Burtovoi, A., Fiori, M., Naletto, G., Spolon, A., Barbieri, C., Papitto, A., Ambrosino, F. 2019, *MNRAS*, *485*, L109.

Zavlin, V. E. 2007, *Ap&SS*, *308*, 297.

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