Optical studies of the companion to the „redback“ pulsar J1908+2105

© D.M. Beronya,[1] A.Yu. Kirichenko,[1,2] S.V. Zharikov,[2] A.V. Karpova,[1] D.A. Zyuzin,[1] Yu.A. Shibanov[1]

[1] Ioffe Institute,
194021 St. Petersburg, Russia
[2] Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 877,
22800 Baja California, México
e-mail: daria.beronya@gmail.com

Received May 12, 2023
Revised July 25, 2023
Accepted October, 30, 2023

The binary millisecond radio- and gamma-ray pulsar J1908+2105 is likely a member of the „redback“ class. Its possible companion has been discovered in the Gaia catalog. To confirm the companion and to obtain parameters of the system, we carried out time-series photometry of the source in the B, V, R, I bands with the 2.1-m OAN-SPM telescope in Mexico. We found its brightness variability with the period of 3.5 h consistent with the pulsar orbital period thus confirming the source association with the pulsar. Amplitudes of the variations are $0.2-0.3^m$, typical for „redbacks“. We also performed optical spectroscopy of the companion with the 10-m Gran Telescopio Canarias. The obtained spectra correspond to a star of spectral class K-M.

DOI: 10.61011/TP.2023.12.57740.f236-23

Introduction

„Spider pulsars“ are a subclass of millisecond pulsars (MSPs) in close binary systems with an orbital period of less than a day and a low-mass companion. The side of the companion star facing the pulsar is heated and vaporized by the pulsar wind, and the vaporized material can cause eclipses of the radio signal from the pulsar. „Spider pulsars“ are divided into „redback spiders“ (redback, RB), whose companions are non-degenerate stars with a mass of $\approx 0.1-1M_\odot$, and „black widows“ (BW), whose companions are partially degenerate stellar remnants with very low mass, $< 0.05M_\odot$ [1].

MSP J1908+2105 (hereafter J1908) was discovered by the Arecibo radio telescope in the course of searching for pulsations of unidentified gamma-ray sources detected by the Fermi [2] observatory. Later, pulsations were detected in the gamma range [3]. The rotation period of the pulsar is 2.56 ms, and the orbital period of the system is 3.5 h. J1908 presumably pertains to the RB systems. The dispersion measure $\mathrm{DM} = 62\,\mathrm{pc/cm^3}$ corresponds to the distance 2.6–3.2 kpc depending on the choice of the model for the distribution of free electrons in Galaxy — YMW16 [4] or NE2001 [5].

The pulsar's companion was identified with an optical source contained in the Gaia [6] catalog. To confirm the companion and determine the parameters of the system, we conducted a series of photometric observations of the source with the 2.1-meter OAN-SPM telescope in Mexico. Also we proposed the optical spectral observations with the 10-meter Gran Telescopio Canarias (GTC). Preliminary results of the data analysis are described below.

1. Photometric Data

Observations with the 2.1-meter OAN-SPM telescope were made in 2018–2022. The obtained data are a series of images with exposures of 600 s in the bands B, V, R, and I. All images were processed in a standard way by means of the IRAF software package. To find the periodicity, we used the Lomb–Scargle algorithm, which allows us to analyze non-uniform time series [7,8], and data in the bands R and V, where the largest number of measurements were made. The periodogram (power spectrum) obtained from the data in the band R is shown in Fig. 1. Its highest peak corresponds to the period 3.51 ± 0.04 h, which is consistent with the orbital period of J1908. The positions of the highest peaks in the data in different bands are also consistent with this period within the error limits. The light curves folded with this period are shown in Fig. 2. The mean values were $B = 23.2^m$, $V = 21.5^m$, $R = 20.6^m$, and $I = 19.6^m$, and the amplitude of variability $\approx 0.2-0.3^m$.

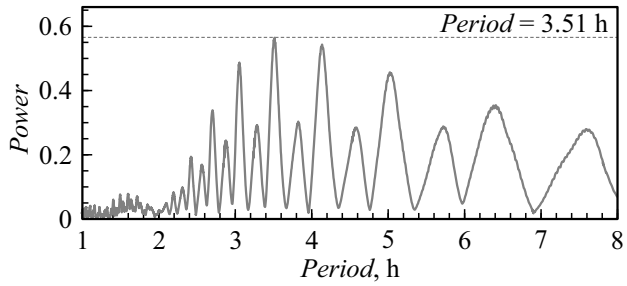

Figure 1. Lomb–Scargle periodogram obtained for data in the band R. The highest peak of the power spectrum corresponds to the orbital period of the system.

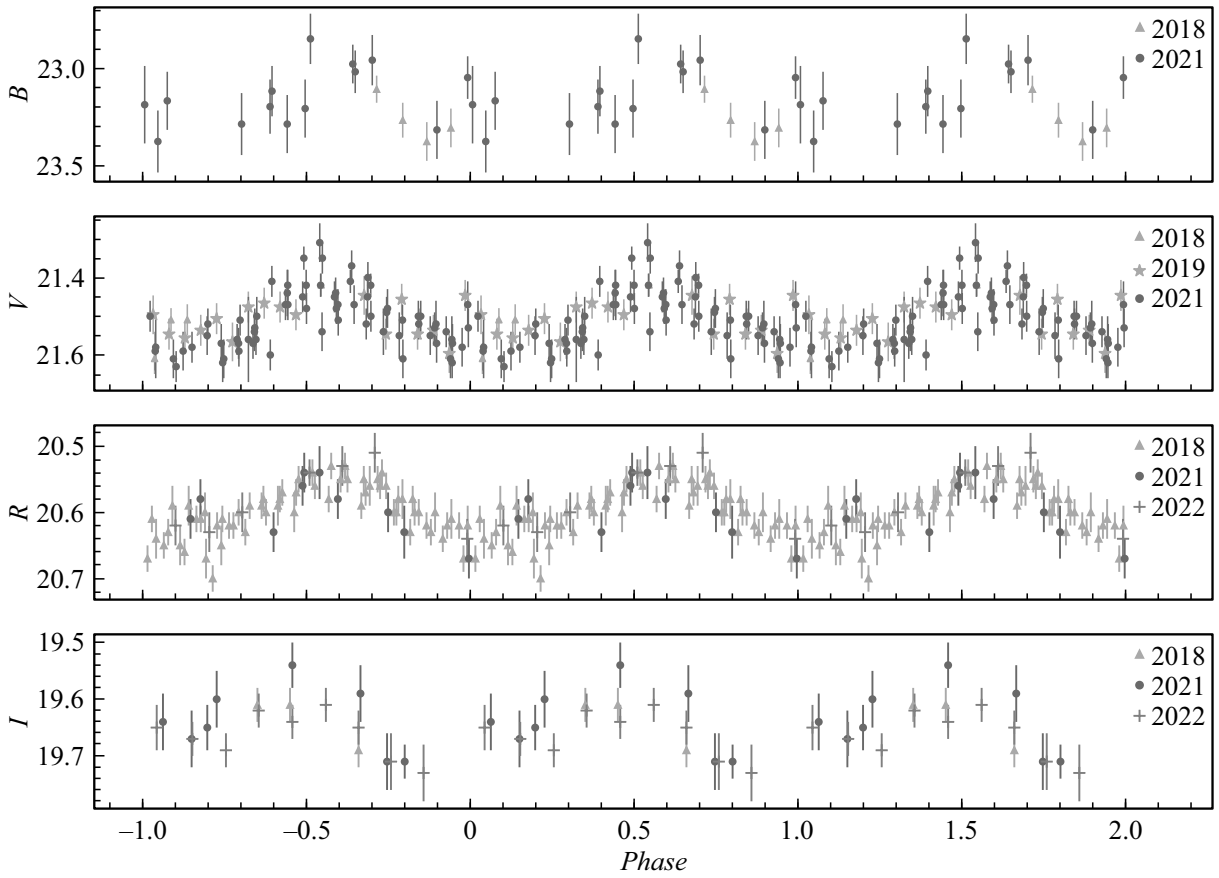

Figure 2. J1908 companion light curves in the bands *BVRI* folded with the orbital period of the system based on the observational data 2018–2022.

2. Spectrum Energy Distribution Parameters

Given the small amplitude of variability, it is appropriate to construct a time-averaged spectral energy distribution of the radiation as a preliminary step in the stellar classification of the companion. In order to cover the widest possible spectral range, we additionally used broadband observations from the Pan-STARRS [9] and Gaia [10] catalogs and analyzed them using the ARIADNE [11] package. As we know, the estimation of distance based on a dispersion measure is inaccurate and can differ from the true value both upwards and downwards, we decided to use a wider dispersion of distances D and defined the source parameters for 2 and 5 kpc. The interstellar absorption of $E(B-V)$ was estimated using a map [12] and $E(B-V)$ was assumed to be fixed for the distance range. For $D = 2$ kpc and $E(B-V) = 0.5^m$, we obtained the effective surface temperature of the star $T_{\text{eff}} = 4600 \pm 250$ K, which corresponds to a star of spectral classes K3–K6, and a radius $R = 0.36 \pm 0.06 R_\odot$. For $D = 5$ kpc and $E(B-V) = 0.64^m$ we get $T_{\text{eff}} = 4900 \pm 300$ K (class K1–K4) and $R = 0.9 \pm 0.1 R_\odot$.

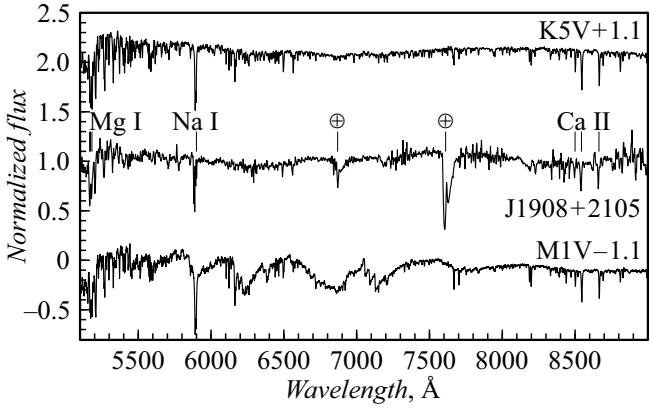

Figure 3. Normalized spectrum of the J1908 companion and stars of spectral classes K5V and M1V. The vertical lines show the position of the triplets Mg I (5167, 5173 and 5183 Å) and Ca II (8498, 8542 and 8662 Å) and the doublet Na I ($\sim$ 5900 Å).

3. Spectral Data

Spectral observations of the companion J1908 were carried out with the GTC in May 2020 using the OSIRIS instrument. 15 spectra with exposures of 815 s were obtained. The data were processed in a standard way

by means of the IRAF software package. The time-averaged and normalized for the spectral flux density in the continuum spectrum is shown in Fig. 3. Comparison with the empirical models of the spectra of dwarfs of classes K5 and M1 [13] indicates that the object belongs to stars of spectral class K–M, which is consistent with the results of spectral energy distribution modelling. In the spectra, we found the triplet lines Ca II and Mg I and the doublet Na I, which are marked in Fig. 3.

4. Discussion

The coincidence of the obtained period of the optical source light curve with the orbital period of J1908 confirms the mutual identification of these objects.

The optical light curves of J1908 are nearly sinusoidal, with one peak per period. The maximum brightness corresponds to the moment when the companion faces the observer with the side heated by the pulsar wind, and the minimum, respectively — cooler far side (e.g., [14]). The amplitudes of the variability in the different bands were about $0.2-0.3^m$, which is typical for systems of the RB type, while the amplitudes of BW are much larger, usually $2-4^m$ [15].

The measured radius of $0.3-1R_\odot$ is also typical for companion stars in RB systems, in the case of BW typical radii $\approx 0.1R_\odot$ [16].

The detection of absorption lines in the companion's spectrum is important for measuring the amplitude of its radial velocities. Considering the parameters based on the pulsar timing in the radio and gamma-ray bands, this will make it possible to estimate the mass ratio of the pulsar and the companion. Using the results of the obtained light curves modelling, we will be able to constrain the parameters of the system, such as the inclination of the orbit, the masses of the components, the temperature distribution over the surface of the companion, the efficiency of pulsar wind irradiation, as well as independently estimate the distance (see, e.g., [15,16]). This, however, is beyond the scope of the present work and will be published in a separate article shortly.

Conclusion

We have conducted photometric and spectral observations of the MSP in the binary system J1908, which possible optical companion was found in the Gaia catalog. Timing analysis of the data showed that the period of the source brightness variation coincides with the orbital period of the pulsar, which proves its association with the pulsar. The amplitude of the light curves is typical for systems of the RB type. The optical spectra of the source and the time-averaged spectral energy distribution indicate that it belongs to the spectral class K–M. The obtained data will be used for the companion light curves and radial velocities modelling and the restriction of the J1908 parameters.

Funding

The research of D.M. Beronya, A.V. Karpova and D.A. Zyuzin was carried out at the expense of a grant from the Russian Science Foundation №22-22-00921, https://rscf.ru/project/22-22-00921/.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M.S.E. Roberts. Proceedings of the International Astronomical Union, **8(S291)**, 127 (2013). DOI: 10.1017/S174392131202337X
[2] H.T. Cromartie, F. Camilo, M. Kerr, J.S. Deneva, S.M. Ransom, P.S. Ray, E.C. Ferrara, P.F. Michelson, K.S. Wood. ApJ, **819**, 34 (2016). DOI: 10.3847/0004-637X/819/1/34
[3] J.S. Deneva, P.S. Ray, F. Camilo, P.C.C. Freire, H.T. Cromartie, S.M. Ransom, E. Ferrara, M. Kerr, T.H. Bumett, P.M. Saz Parkinson. ApJ, **909**, 6 (2021). DOI: 10.3847/1538-4357/abd7a1
[4] J.M. Yao, R.N. Manchester, N. Wang. ApJ, **835**, 29 (2017). DOI: 10.3847/1538-4357/835/1/29
[5] J.M. Cordes, T.J.W. Lazio. Preprint, arXiv:astro-ph/0207156 (2002). DOI: 10.48550/arXiv.astro-ph/0207156
[6] J. Strader, S. Swihart, L. Chomiuk, A. Bahramian, C. Britt, Ch. Britt, C.C. Cheung, K. Dage, J. Hapern, K.-L. Li, R.P. Mignani, J.A. Orosz, M. Peacock, R. Salinas, L. Shishkovsky, E. Tremou. ApJ, **872**, 42 (2019). DOI: 10.3847/1538-4357/aafbaa
[7] N.R. Lomb. Ap&SS, **39**, 447 (1976). DOI: 10.1007/BF00648343
[8] J.D. Scargle, ApJ, **263**, 835 (1982). DOI: 10.1086/160554
[9] H.A. Flewelling, E.A. Magnier, K.C. Chambers, J.N. Heasley, C. Holmberg et al. ApJS, **251**, 7 (2020). DOI: 10.3847/1538-4365/abb82d
[10] G. Collaboration, A. Vallenari, A.G.A. Brown, T. Prusti, J.H.J. de Bruijne, et al. A&A (2022). DOI: 10.1051/0004-6361/202243940
[11] J.I. Vines, J.S. Jenkins. MNRAS, **513**, 2719 (2022). DOI: 10.1093/mnras/stac956
[12] G.M. Green, E. Schlafly, C. Zucker, J.S. Speagle, D. Finkbeiner. ApJ, **887**, 93 (2019). DOI: 10.3847/1538-4357/ab5362
[13] A.Y. Kesseli, A.A. West, M. Veyette, B. Harrison, D. Feldman, J.J. Bochanski. ApJS, **230**, 16 (2017). DOI: 10.3847/1538-4365/aa656d
[14] S.J. Swihart, J. Strader, L. Chomiuk, E. Aydi, K.V. Sokolovsky, P.S. Ray, M. Kerr. ApJ, **941**, 199 (2022). DOI: 10.3847/1538-4357/aca2ac
[15] P. Draghis, R.W. Romani, A.V. Filippenko, T.G. Brink, W. Zheng, J.P. Halpern, F. Camilo. ApJ, **883**, 108 (2019). DOI: 10.3847/1538-4357/ab378b
[16] S. Zharikov, A. Kirichenko, D. Zyuzin, Yu. Shibanov, J.S. Deneva. MNRAS, **489**, 5547 (2019). DOI: 10.1093/mnras/stz2475

Translated by 123