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# 4FGL J2054.2+6904: a binary „redback“pulsar

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The $\gamma$-ray source 4FGL J2054.2+6904 discovered with *Fermi* was recently classified as a pulsar candidate. Its possible X-ray and optical counterpart was identified with *Swift*. Using Zwicky survey data we show that the counterpart is variable in the optical with the period of about 7.5 h. The shape of the light curve is almost sinusoidal with the amplitude of $\approx 0.5^m$. The spectral energy distribution corresponds to the stellar spectrum with the effective temperature of $5820 \pm 410$ K. We also firmly detected the source in X-rays using the *SRG/eROSITA* all sky survey data. Its X-ray spectrum can be described by a power law with the photon index of about 1.0 and unabsorbed flux $\approx 2 \cdot 10^{-13}$ erg/(s $\cdot$ cm$^2$) in the 0.5−10 keV range. These results show that 4FGL J2054.2+6904 is a promising candidate to a millisecond pulsar in a close binary system of the „redback“ type.

**Keywords**: neutron stars, binary systems, millisecond pulsars.

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## Introduction

Millisecond pulsars (MSPs) — are a subclass of pulsars with rotational periods less than 30 ms. Of great interest are „pulsars−spiders“ — MSPs in close binary systems with an orbital period of less than a day and a low-mass companion whose side facing the pulsar is heated and evaporated by the pulsar wind. They are subdivided into „black widow“ (black widow, BW) and „redback spiders“ (redback, RB) [1]. Companions of RB are non-degenerate stars with a mass of $M_c \approx 0.1{-}1 M_\odot$, and BW — partially degenerate stars with a mass of $M_c < 0.05 M_\odot$. Vaporized matter in a number of such systems results in regular eclipses of the emission from pulsar.

The gamma-ray source 4FGL J2054.2+6904 (hereinafter J2054), discovered by the Fermi Observatory, was recently classified as a pulsar candidate [2]. With the help of the Swift Observatory, its potential X-ray and optical counterpart was found. In this paper, we briefly describe the results of the analysis of previously unused archival optical and X-ray data, clarifying the nature of this source.

## 1. Optical Data Analysis

We found (see [3] for details) that the counterpart candidate of J2054 is present in the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) [4], Zwicky Transient Facility (ZTF) [5], Gaia [6], and Transiting Exoplanet Survey Satellite (TESS) [7]. Its coordinates are R.A = 20 : 53 : 58.99298(7) and Dec. = +69 : 05 : 19.7063(5). The magnitudes taken from the Pan-STARRS catalog are $g = 20.8$, $r = 20.1$, $i = 19.7$, $z = 19.6$ , and $y = 19.4$, and the effective temperature is $T_{\rm eff} = 5820 \pm 410$ K [7]. According to the Gaia catalog and the work [8], the minimum distance to the object is 1.5 kpc, and maximum — 5.3 kpc.

The ZTF catalog contains a sufficient number of optical measurements to perform timing analysis. We used data in the $r$ band, where there are the largest number of points, and the Lomb–Scargle method [9,10] to find the periodicity. The largest peak in the periodogram corresponds to a period of about 7.5 h (Fig. 1). The light curves in the $g$ and $r$ bands, folded with the found period, are shown in Fig. 2.

## 2. X-ray Data Analysis

As already reported, the X-ray counterpart candidate of J2054 was detected in the Swift data. We also found it in

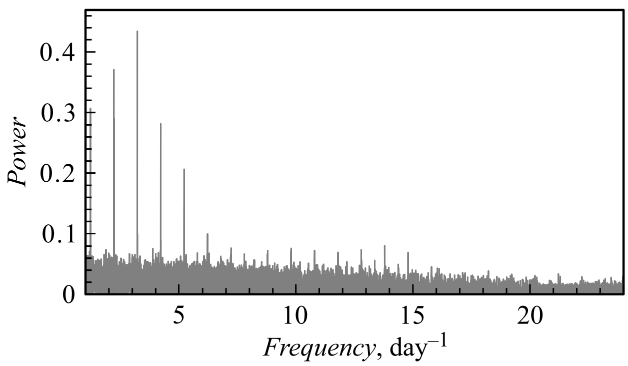


**Figure 1.** Lomb–Scargle periodogram of the J2054 light curve derived from ZTF data in the $r$ band.

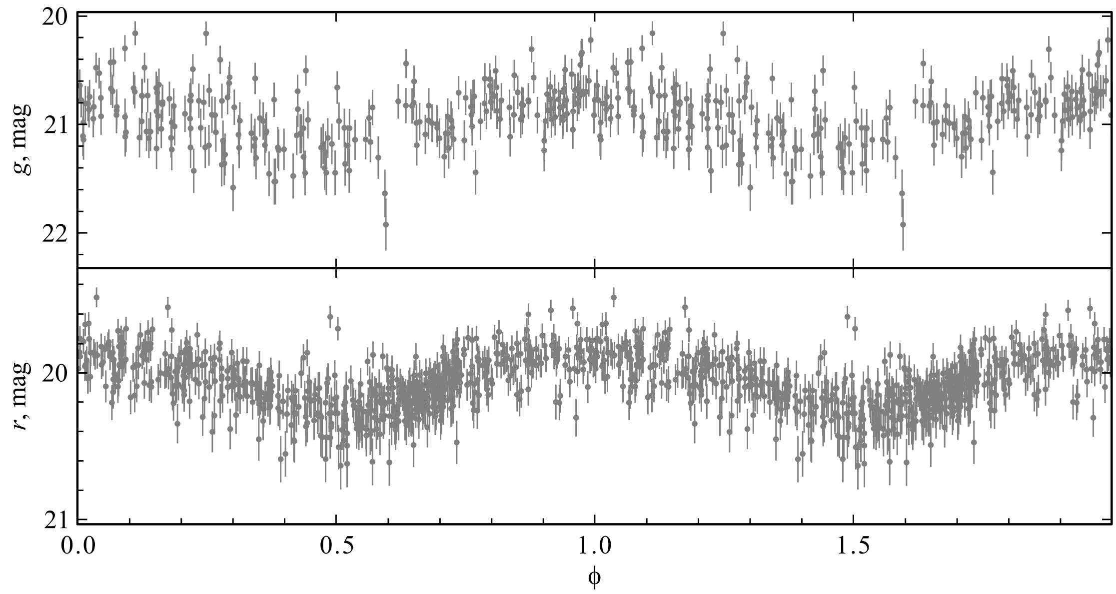


**Figure 2.** Brightness variations of J2054 optical counterpart candidate as a function of orbital phase $\varphi$ from ZTF data in $g$ and $r$ bands.

the X-ray all-sky survey performed by the SRG/eROSITA telescope [11].

To extract the spectrum from the Swift data, we used tools available on the telescope's website [12,13]. The resulting spectrum contained 32 counts from the source in the range 0.3–10 keV and was grouped to contain at least one count in the spectral bin. In the case of eROSITA, 64 source counts were grouped to have at least three counts per spectral bin.

We approximated both spectra simultaneously using $C$-statistic [14] in the 0.3–10 keV range. To account for interstellar absorption, we used tbabs model with wilm abundances [15]. We used the color excess of $E(B-V) = 0.37$ for J2054 obtained from the absorption map [16] and the ratio from the work [17], in order to obtain the value of the column density of absorbing hydrogen $N_{\mathrm{H}}$, which was $3.3 \cdot 10^{21}\,\mathrm{cm}^{-2}$. This value was fixed during the approximation procedure. We found that the spectrum can be well described by a power law with a photon index $\Gamma = 1.0 \pm 0.3$ and an absorption-corrected flux in the range 0.5–10 keV $F_X = 1.7^{+0.5}_{-0.3} \cdot 10^{-13}\,\mathrm{erg/(s \cdot cm^2)}$ (the uncertainties correspond to a confidence interval of 68%).

## 3. Discussion

As shown by the ZTF catalog data, the optical counterpart candidate of J2054 is a variable source with a period of about 7.5 h, which we can interpret as the orbital period of the binary system. This value is typical for the systems RB and BW [18,19].

The resulting optical light curves are close to sinusoidal, with one wide peak per period. The light curves of „spider pulsars" can show one or two peaks per period. The two peaks are explained by the deformation of the companion star under the influence of tidal forces, as a result of which it acquires an elongated shape. The change in brightness occurs due to the fact that the apparent surface area of the star changes as it moves along the orbit. One peak per period occurs when the effect of irradiation of the companion by the pulsar is more significant than its deformation. Then, the maximum of the light curve corresponds to the heated side of the companion facing the pulsar, and — the minimum of — cooler opposite side (e.g., [19]). Variations in the brightness of the J2054 counterpart candidate are approximately $0.5^m$. This amplitude of variability is more typical for RB, whose amplitude is usually $< 1^m$, whereas for BW — $2{-}4^m$ [20].

The temperature of the optical source, according to the Gaia catalog, is $T_{\mathrm{eff}} = 5820 \pm 410\,\mathrm{K}$, which corresponds approximately to the spectral class G1. Such temperatures are observed in companion stars in the RB and BW [18,20] systems.

The X-ray spectrum of the counterpart candidate of J2054 can be described by a power law, which is typical for „pulsars–spiders" [18,19]. This non-thermal radiation is explained by the acceleration of the particles by the shock wave generated by the interaction of the pulsar wind and the star wind of the companion. Orbital modulation of X-rays can be observed, but the small number of counts in the case of J2054 does not allow this to be verified. The measured flux in the range 0.5–10 keV for the available distance estimate 1.5–5.3 kpc corresponds to the luminosity $L_X = (0.4{-}7.4) \cdot 10^{32}\,\mathrm{erg/s}$. Such values are more typical for RB systems than BW, as well as the resulting photon index $\Gamma = 1.0 \pm 0.3$ [19].

## Conclusion

We have discovered a possible optical counterpart of the gamma-ray source J2054. According to the optical and X-ray properties of the source, J2054 is a promising candidate for binary star systems of the „redback" type. To confirm this, it is necessary to obtain better light curves in several bands and model them to determine the parameters of the system: the masses of the components, the inclination of the orbit, the Roche lobe filling factor and the efficiency of pulsar wind irradiation.

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## Conflict of interest

The authors declare that they have no conflict of interest.

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