Search for the optical counterparts of the γ-ray pulsars J2055+2539, J2043+2740, J1957+5033

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Abstract. First optical observations of γ-ray pulsars J2055+2539, J2043+2740, J1957+5033 have been obtained with the BTA 6m optical telescope. We found no reliable counterpart candidates to these pulsars. However, upper limits on optical fluxes were derived. Comparison of PSR J2055+2539 and PSR J2043+2740 optical limits and their X-ray spectral data likely suggests the presence of spectral breaks between the optical and X-rays in the multiwavelength emission of these pulsars. X-ray spectral data for PSR J1957+5033 are not yet available. In spite of rather deep Hα-observations of PSR J2055+2539, a bow shock nebula, which was expected for the pulsar, has not been detected. Probably, the density of the interstellar medium surrounding the pulsar is not enough for a bright Hα bow shock to be formed. We also find the further deeper observations of pulsars J2055+2539 and J2043+5740 are reasonable, while a large gamma-ray position error ellipse for J1957+5033 is crowded by background sources and its coordinates should be updated using X-ray observations before any further optical study.

1. Introduction
Rapidly rotating, highly magnetized neutron stars are able to accelerate charged particles to extreme energies (of the order of some TeVs) unattainable in terrestrial accelerators. As a result, they are able to produce an emission in the γ-ray band.

Before the launch of the Fermi Large Area Telescope only 6 pulsars were known as γ-ray emitters. All of these have been identified also at optical wavelengths. The second Fermi LAT catalogs was published in 2013 and included 117 γ-ray pulsars unveiled in three years of observations. Only for 38 of these pulsars did optical observations carry out [1].

Optical investigations of pulsars enable to provide more accurate distance estimations. They are also necessary to obtain multiwavelength spectra, that is important for creating appropriate models of pulsar radiation.

In this work, we focus on searching for optical counterpart candidates to pulsars J2055+2539, J2043+2740 and J1957+5033. Certain parameters of pulsars are summarized in Table 1. These are equatorial \(\alpha_{2000}, \delta_{2000}\) and galactic \(l, b\) coordinates, rotation periods \(P\), period derivatives \(\dot{P}\), characteristic ages \(\tau\), surface magnetic fields \(B\) and spin down energy loss rates \(\dot{E}\).

PSR J2043+2740 was discovered in the radio in the Arecibo millisecond-pulsar survey at 430 MHz in 1994 [2]. In 2010 Abdo et al. published the results of the first six month of Fermi data analysis, containing γ-ray high-confidence pulsation parameters for this pulsar [3].
Table 1. Parameters of pulsars J2055+2539, J2043+2740, J1957+5033.

| PSR     | $\alpha_{2000}, \delta_{2000}$       | $l, b$    | $P, s$    | $\dot{P}, 10^{-15}$ | $\tau, \text{Myr}$ | $B, 10^{12} \, \text{G}$ | $\dot{E}, 10^{33} \, \text{erg s}^{-1}$ |
|---------|--------------------------------------|-----------|-----------|---------------------|---------------------|-----------------------------|-----------------------------------------------|
| J2055+2539 | 20°55′58″.48′.8  +25°40′02″′          | 70°69′.32 | 4.08 ± 0.11 | 1.24                | 1.16               | 4.9                         |                                               |
| J2043+2740 | 20°43′43″.5  +27°56′56″′          | 70°61′.01 | 1.27 ± 0.01 | 1.2                 | 0.354              | 5.6                         |                                               |
| J1957+5033 | 19°57′38″.9  +50°33′18″′          | 84°58′.38 | 7.08 ± 0.05 | 0.839               | 1.65               | 5.3                         |                                               |

PSR J2055+2539 and PSR J1957+5033 were discovered in $\gamma$-rays in a blind frequency search using 11 months of data acquired by the Fermi LAT [4].

The observations in X-rays were performed for all of these pulsars. PSR J2043+2740 was observed in 2002 with XMM-Newton for a total on-source time of 17 ks and detected in the 0.3 – 10 keV energy band at high level of significance. PSR J2055+2539 was also observed with XMM-Newton (0.2–12 keV) using 26 and 136 ks of data taken in 2009 and 2013, respectively. These observations allowed to determine its position and revealed a bright comet-like trail behind the pulsar. Of particular interest in this case is H$\alpha$-imaging, which enables pulsar bow shocks to be detectable. PSR J1957+5033 was observed with Chandra in 2014, but the data are not yet available.

Figure 1. XMM-Newton X-ray archival images of the regions around PSR J2055+2539 using data obtained in 2009 (a) ([4], ObsID 0605470401) and 2013 (b) (ObsID 0724090101). The color scale is in counts per square arcsecond. The green ellipse and the red x mark represent the best pulsar location derived from pulsar timing.

2. Optical observations

The fields of the pulsars J2055+2539, J2043+2740 and J1957+5033 were observed on August 3, 2013 with the multi-mode focal reducer SCORPIO of the BTA, a 6 meter aperture optical telescope at the Special Astrophysical Observatory. Data binning of 2×2 was applied resulting to the pixel scale of 0′.357. The observing conditions were photometric with seeing varied from 2.0 to 2.8. Parameters of filters we used are shown in Table 2. The online version of the article is supplemented with an attached file including the summary of the BTA observations.

Data reduction was performed in a standard way by means of IRAF tools. Imalign task from ctiocal IRAF package was used in order to align images for each filter before combining
them. Stacking of images was performed applying `avsigclip` algorithm with no scaling or weighting. Astrometrical calibration was made with `ccmap/ccsetwcs` IRAF tasks using the positions of about 10 bright, but non-saturated field stars from USNO-B1.0 catalogs, having the nominal accuracy of 0\'\'24. After removing the stars with large residuals 1\(\sigma\) rms-errors were about 0\'\'07–0\'\'1 in RA and 0\'\'05–0\'\'08 in Dec for the fields of the three pulsars. For our pulsars 1\(\sigma\) `Fermi` position uncertainty is typically grater that 1\(\prime\) and below we neglect much smaller astrometric referencing uncertainties of the optical images. For the photometric calibrations in the FN657 and SED707 filters we used the GD248 photometric standard star (Oke, 1990), taken in the same night as the targets. Since no photometric standard were observed in VR\(_c\) bands, the photometric calibration in these filters was performed using stars from astrometric catalogs.

### Table 2. Parameters of optical filters.

| Filter  | \(T_{max}\), % | \(\lambda_c\), Å | FWHM, Å | Function                                      |
|---------|----------------|-----------------|--------|----------------------------------------------|
| V       | 49             | 5470            | 790    |                                              |
| R\(_c\) | 54             | 6620            | 1500   | pulsar detection in the optical continuum   |
| SED707  | 77             | 7040            | 207    |                                              |
| FN657   | 73             | 6555            | 75     | pulsar bow shock detection in the H\(_{\alpha}\) |

#### 2.1. PSR J2055+2539 observations

The pulsar field was observed in the V, R\(_c\), FN657 and SED707 bands with total exposures of 120s, 360s, 1800s and 300s, respectively (Figures 2, 3).

**Figure 2.** a) 1\'5 x 1\'5 image fragment of the PSR J2055+2539 field. b) Intersection of 3\(\sigma\) uncertainty ellipses of the `Fermi` (1) and `XMM-Newton` (2, 3 - according to the data of 2009 and 2013, respectively) pulsar positions marked on the 0\'5 x 0\'5 image fragment of the pulsar field.

**Figure 3.** 0\'4 x 0\'4 PSR J2055+2539 vicinity in the four bands.
There are three objects within or just off the uncertainty ellipse. Objects 1 and 2 are obviously background stars, which can be found in the astrometrical catalogs. Taking into account errors their magnitudes obtained with aperture photometry coincided with ones of the catalogs. Source 3 is fainter and absent in catalogues. Further studies are necessary to reveal its nature. Our results of aperture photometry for sources 1,2,3 are presented in Table 3.

**Table 3.** The results of aperture photometry of the three objects visible in Figure 3.

| Object | \( \alpha_{2000} \) | \( \delta_{2000} \) | FN657 | SED707 | V  | Rc  |
|--------|-------------------|------------------|-------|--------|----|-----|
| 1      | 20:55:49.1        | +25:39:59.7      | 19.1±0.2 | 19.24±0.11 | 20.13±0.56 | 19.18±0.28 |
| 2      | 20:55:48.3        | +25:40:11.6      | 18.0±0.2 | 18.15±0.11 | 18.77±0.56 | 18.18±0.28 |
| 3      | 20:55:48.9        | +25:39:52.9      | 21.64±0.21 | 21.83±0.13 | 22.48±0.56 | 21.64±0.29 |

Based on the image in the FN657 band it is not obviously possible to conclude the detection of \( \text{H}_\alpha \) bow shock emission. Apparently, the density of the interstellar medium surrounding this high Galactic altitude pulsar is not enough for a bright \( \text{H}_\alpha \) bow shock to be formed.

### 2.2. PSR J1957+5033 observations

The pulsar field was observed in the V, R, FN657 and SED707 bands with total exposures of 120s, 60s, 1200s and 600s, respectively (Figure 4).

**Figure 4.** a) 2’ × 2’ image fragment of the PSR J1957+5033 field. b) 1’25 × 1’25 pulsar vicinity in the four bands. 1σ and 3σ pulsar *Fermi* position error ellipses are shown.

Two stars are seen within 1σ *Fermi* error ellipse. They are marked as 1 and 2 in Figure 4. Their parameters can be found in the astrometrical catalogs (Table 4).

**Table 4.** Parameters of stars 1 and 2 marked in Figure 4, taken from astrometrical catalogs.

| Object | \( \alpha_{2000} \), \( \delta_{2000} \) | \( B \) USNO-A2.0 | \( R \) USNO-A2.0 | \( B \) Nomad | \( R \) Nomad | \( V \) GSC 2.3 | \( R \) GSC 2.2 |
|--------|-----------------|-----------------|-----------------|--------|--------|--------|--------|
| 1      | 19:57:39.135 +50:33:20.6 | 17 | 16.8 | 17.25 | 16.58 | 17.11 | 16.54±0.24 |
| 2      | 19:57:38.786 +50:33:26.9 | – | – | 19.56 | 19.68 | – | – |
The identification of PSR J1957+5033 is complicated by large Fermi positional errors and many stellar objects within 3σ uncertainty ellipse. However, X-ray observation made by the ACIS-S instrument on the Chandra telescope, having a spatial resolution of 0′′.5, will enable to narrow down the region of the expected pulsar position.

2.3. PSR J2043+2740 observations

The pulsar field was observed in the Rc, FN657 and SED707 bands with total exposures of 180s, 600s and 300s, respectively (Figures 5). An extended source is detected on the border of the 3σ pulsar ellipse (Figure 5). The object is not included in any astrometrical catalog. We performed aperture photometry on the source. Its magnitude is \( R_c = 21.01 \pm 0.09 \). It is also visible in FN657 and SED707 bands, while its relation to the pulsar remains unclear.

![Figure 5](image)

**Figure 5.** a) 1′ × 1′ image fragment of the PSR J2043+2740 field. b) 0.2′ × 0.2′ pulsar vicinity in the three bands.

3. The upper limits on the optical flux

We have not detected any plausible pulsar optical counterpart or signature of the Hα bow shock for all three pulsars observed with the BTA. 3σ detection limits estimated by a standard way are given in Table 5. Interstellar extinctions for each pulsar were inferred from X-ray data, the total Galactic extinction and HI column density for given directions, and pulsar distance estimates.

| PSR      | \( V_{(F_{lim}, \, \mu\text{Jy})} \) | \( R_c_{(F_{lim}, \, \mu\text{Jy})} \) | \( FN657_{(F_{lim}, \, \mu\text{Jy})} \) | \( SED707_{(F_{lim}, \, \mu\text{Jy})} \) |
|----------|-----------------------------------|-------------------------|-----------------|------------------|
| J2055+2539 | 22.78 (5.354)                     | 23.22 (2.57)            | 22.75 (4.935)   | 22.77 (4.591)    |
| J1957+5033 | 23.07 (2.931)                     | 22.61 (3.512)           | 22.66 (4.13)    | 23.22 (2.408)    |
| J2043+2740 | –                                 | 21.67 (11.718)          | 21.87 (12.141)  | 22.44 (6.773)    |

4. Multiwavelength observations of pulsars J2055+2539, J1957+5033, J2043+2740

In order to compare the obtained flux upper limits with available information about X-ray and γ-ray spectra we have carried out multiwavelength spectral analysis for each pulsar. We used the results of XMM-Newton observations of pulsars J2043+2740 [5] and J2055+2539 (ObsID 0724090101) for the X-rays, and the Fermi online catalog, containing the γ-ray spectral
parameters [1]. The X-ray and γ-ray spectra are best fitted by a pure power law and an exponentially cut-off power law, respectively. The parameters of fits are listed in the attached file. The unabsorbed multiwavelength spectra are shown in Figure 6.

![Multiwavelength spectra of pulsars J2055+2539, J2043+2740, J1957+5033. The detection ranges are marked by horizontal bars. The optical detection limits are marked by horizontal bars with arrows. Solid lines show the best-fit spectral models to the XMM-Newton and Fermi data, extrapolated towards the optical range (dashed line). The shaded regions correspond to 1σ uncertainties of the fits.](image)

**Figure 6.** Multiwavelength spectra of pulsars J2055+2539, J2043+2740, J1957+5033. The detection ranges are marked by horizontal bars. The optical detection limits are marked by horizontal bars with arrows. Solid lines show the best-fit spectral models to the XMM-Newton and Fermi data, extrapolated towards the optical range (dashed line). The shaded regions correspond to 1σ uncertainties of the fits.

5. Conclusions
We presented the results of the first optical observations of the γ-ray pulsars J2055+2539, J2043+5740, J1957+5033, taken with the BTA. Although the pulsars are undetected at our rather short exposures, the derived optical flux upper limits appear to be informative. In case of PSR J2055+2539 and PSR J2043+5740, an inspection of multiwavelength spectra likely suggests a break between X-ray nonthermal power law component and the optical range. In [6], it is assumed that each pulsars nonthermal spectrum can be empirically described by a single power law stretching across many orders of magnitude in frequency, with a break or cut-off at GeV energies. As it is seen from Figure 6, the BTA upper limits are 3-5 orders of magnitude higher than γ-ray extrapolation toward to the optical range, what makes the suggested dependence to be consistent with our data. In spite of an 30 minute total exposure of the combined Hα image of PSR J2055+2539, the expected bow shock has not been detected. Probably, this high-altitude pulsar is surrounded with the low-density interstellar medium, which cannot produce a detectable bow shock. We also find the further deeper optical observations of pulsars J2055+2539 and J2043+5740 are reasonable, while J1957+5033 position should be improved based on Chandra observations.

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