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Deep optical observations of the gamma-ray pulsar J2055+2539 with the GTC

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Abstract. The report gives a broad outline of deep, down to a 28 magnitude limit, optical observations of the γ -ray pulsar J2055+2539 (total exposure time ≈ 7.9 ks), which were obtained with the Gran Telescopio Canarias in the g' -band. To derive the most precise pulsar position we utilized recent *Chandra* observations, where the pulsar X-ray counterpart is detected with high significance. Using two reference stars detected both in the optical and X-rays we improved the absolute astrometry accuracy for the *Chandra* image of the PSR J2055+2539 field. The resulting *Chandra* pulsar position error circle of about $0''.2$ is compatible with the 1σ *Fermi* position of the pulsar ($0''.5$), obtained from timing analysis.

No optical counterpart was detected within the refined pulsar error circle. However, we managed to correct a shallow upper limit on the optical flux of the pulsar, which had been derived from preliminary observations. The new value $g' = 26.6$. It is brighter than the limit stated above due to the presence of a nearby star, $0''.8$ from the pulsar, with $g' = 20.3$. The inspection of the pulsar multiwavelength spectrum suggests a break between the optical and X-rays.

1. Introduction

PSR J2055+2539 (hereafter, J2055) was discovered in a blind frequency search using data from the *Fermi* Large Area Telescope (LAT) in 2009 [1]. The pulsar is located high above the Galactic plane ($b = -12^\circ 52'$), that implies a low interstellar absorption and thereby facilitates the observations in other spectral wavelengths. Based on the timing analysis of the *Fermi* LAT data it was determined that the pulsar has a spin period P of 0.32 s and a spin period derivative \dot{P} of 4×10^{-11} . Thus, the pulsar seems relatively old with a characteristic age $\tau = 0.5P\dot{P}^{-1}$ of 1.24 Myr. J2055 is one of the least energetic *Fermi* LAT pulsars with a spin-down energy loss rate $\dot{E} = 5 \times 10^{33}$ erg s⁻¹. However, it makes the list of the 100 brightest γ -ray sources with the observed γ -ray energy flux of about 5.5×10^{-11} erg cm⁻² s⁻¹ [2]. The pulsar distance of 0.58 kpc can be estimated from γ -ray pseudo-distance relation [1]. That all makes this source appealing in terms of multiwavelength search.

Shortly after the discovery the follow-up observations were carried out using the *Arecibo* radio telescope at 327 MHz, however no pulsed emission have been detected [3]. Short-exposure data from XMM-*Newton*, obtained in 2009 and 2010, enabled to identify the pulsar with the X-ray source XMMU J205549.4+253959 [1]. Additional XMM-*Newton* observations, performed in 2013 for a total time of 135.2 ks, revealed a bright cometlike tail extending to the south of the



pulsar (figure 1) [3]. In 2015, the high spatial resolution observations of J2055 were performed with the ACIS instrument on board the *Chandra* observatory (figure 2).

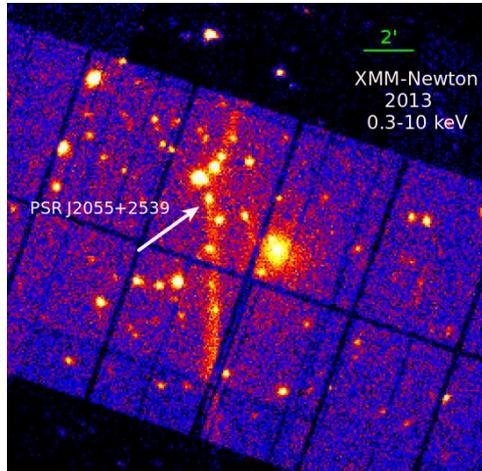


Figure 1. The X-ray image of the PSR J2055+2539 field resulting from merging all *XMM-Newton* observations [3].

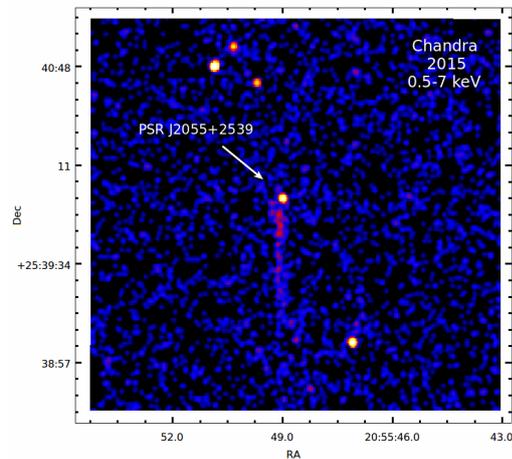


Figure 2. 2.5×2.4 image fragment of the PSR J2055+2539 field, derived from the archival data of 96.8 ks *Chandra* observations (ObsID 16957).

The presence of the cometlike tail gave a reason to suspect that the pulsar velocity is high enough to produce a detectable H_α bow shock nebula around the pulsar. In view of that possibility optical observations are particularly valuable. In 2013 we conducted the preliminary optical search for J2055 and its nebula with the *BTA* using broadband V, R_c and narrowband H_α filters. Neither the pulsar, nor the bow shock was detected [4]. The derived optical flux upper limits were close to a magnitude of 23 ($V = 22.8$, $R_c = 23.2$).

2. Observations of the PSR J2055+2539 field with the GTC

We undertook deep optical observations with the Gran Telescopio Canarias (*GTC*) for a more detailed inspection of the J2055 vicinity. The data were obtained in three *GTC* observations, executed on 16, 19 and 24 August, 2014. The pulsar field was imaged in the Sloan g' band ($\lambda_C = 481.5$ nm, FWHM = 153 nm) with the Optical System for Imaging and low Resolution Integrated Spectroscopy (OSIRIS). Nine exposures of 291 s each and one short frame of 10 s were taken on every night of the observations. In total, about 8 ks of time were obtained for the target, with an average seeing of $0''.7$.

Standard processing steps such as bias subtraction, flatfielding, image aligning and stacking were done using *IRAF* packages. The resulting image is depicted in figure 3. To perform the astrometric calibration of the resulting image we used 12 reference stars included in the USNO-B1.0 catalogue and then carried out the fit by means of *ccmap/ccsetwcs* algorithms. For the 7 most reliable stars left after iterative removal of outliers, we obtained 1σ rms errors of $0''.08$ and $0''.09$ in RA and Dec, respectively. Taking into account the nominal USNO accuracy of $0''.2$, we found the resulting error of the astrometric calibration of about $0''.23$. Combining this value with the *XMM-Newton* or *Fermi* LAT position uncertainties, we estimated the 3σ pulsar position errors in the *GTC* image of $5''.4$ for the former instrument and $1''.65$ for the latter one. Both error circles are shown in figure 3.

High spatial resolution of the *Chandra* image enabled us to strongly constrain J2055 position. The nominal accuracy of the *Chandra* astrometry is $0''.6$. In order to correct the *Chandra* absolute

astrometry we chose two optical sources J205550.31+254055.5 and J205550.85+254048.2, contained both in the SDSS7 catalogue (the first one is also known as USNO-B1.0 1156-0496126). These objects were identified with two X-ray sources (RA 20:55:50.3, Dec +25:40:55 and RA 20:55:50.8, Dec +25:40:48, respectively) in the *Chandra* image. We used a couple of mutually aligned *GTC* images of 10 s and 600 s to obtain more accurate reference stars coordinates. The referencing between the *Chandra* and *GTC* images was performed with the `celldetect/wcs_match` tools from the CIAO package. Considering the distance of the X-ray counterparts from the ACIS aimpoint of $1'$, we neglected any distortion effects. The total astrometry errors and the improved WCS coordinates of the pulsar are given in the third column of table 1. The resulting 3σ *Chandra* error ellipse is shown in figure 3.

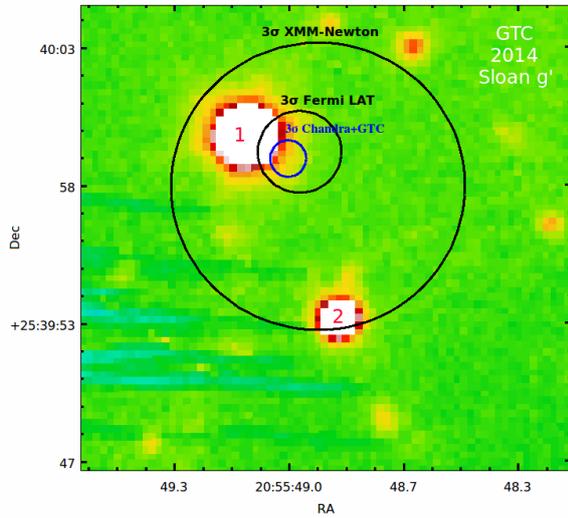


Figure 3. $0'.3 \times 0'.3$ image fragment of the J2055 field, observed with the *GTC*. The black circles indicate the 3σ pulsar position uncertainties computed from the *XMM-Newton* observations and *Fermi* timing analysis. The blue ellipse marks the J2055 3σ position error, derived from *Chandra* absolute astrometry correction.

Table 1. *XMM-Newton*, *Fermi* and *Chandra* (after astrometric correction using the *GTC* images) positions of J2055. 1σ errors are taken in brackets.

	<i>XMM-Newton</i>	<i>Fermi</i> LAT	<i>Chandra+GTC</i>
RA _{J2000}	20 ^h 55 ^m 48 ^s .89(1''.8)	20 ^h 55 ^m 48 ^s .94(0''.5)	20 ^h 55 ^m 48 ^s .97(0''.22)
Dec _{J2000}	+25°39'57''.8(1''.8)	+25°39'59''.1(0''.5)	+25°39'58''.85(0''.23)

We found out that the corrected 3σ *Chandra* error ellipse region is contaminated by a nearby bright star $0'.8$ from the pulsar position (object 1 in figure 3). No reliable counterpart for J2055 was revealed in that ellipse. To provide a detection limit measurements we performed the photometric calibration using the standard star from the SA 109 field [5], observed at the third night of the *GTC* observations. The photometric zeropoint is 28.70 ± 0.05 . Then we derived the 3σ detection limit [6] in the g' -band of 26.6 magnitude. We also conducted the aperture photometry for two bright stars within the *XMM-Newton* 3σ error circle, marked 1 and 2 in figure 3. For these objects the magnitudes of 20.3 and 22.3 respectively are consistent with SDSS7 measurements.

3. Multiwavelength spectrum of PSR J2055+2539

The XMM-Newton spectral data of J2055 are fitted well by an absorbed power law model, resulting in the absorbing column density N_H of $(2.18 \pm 0.26) \times 10^{21} \text{ cm}^{-2}$ and the photon index $\Gamma = 2.36 \pm 0.14$ [3]. To include the derived upper limit on the J2055 optical brightness in multiwavelength spectral analysis we carried out a magnitude to flux conversion, correcting it for the effects of interstellar absorption [7], using relation between N_H and the optical extinction A_V from [8], and then taking into account $AB_{off} = 0$ for the SDSS photometric system [9]. We obtained the conservative A_V of 1.5. Exponential cut-off power law is an appropriate model for the *Fermi* data [2]. Figure 4 illustrates the unabsorbed multiwavelength spectrum of J2055. The dereddened *GTC* upper limit of $0.47 \mu\text{Jy}$ confirms the suggestion of the spectral break between the optical and X-rays, which is typical for rotation powered pulsars [4].

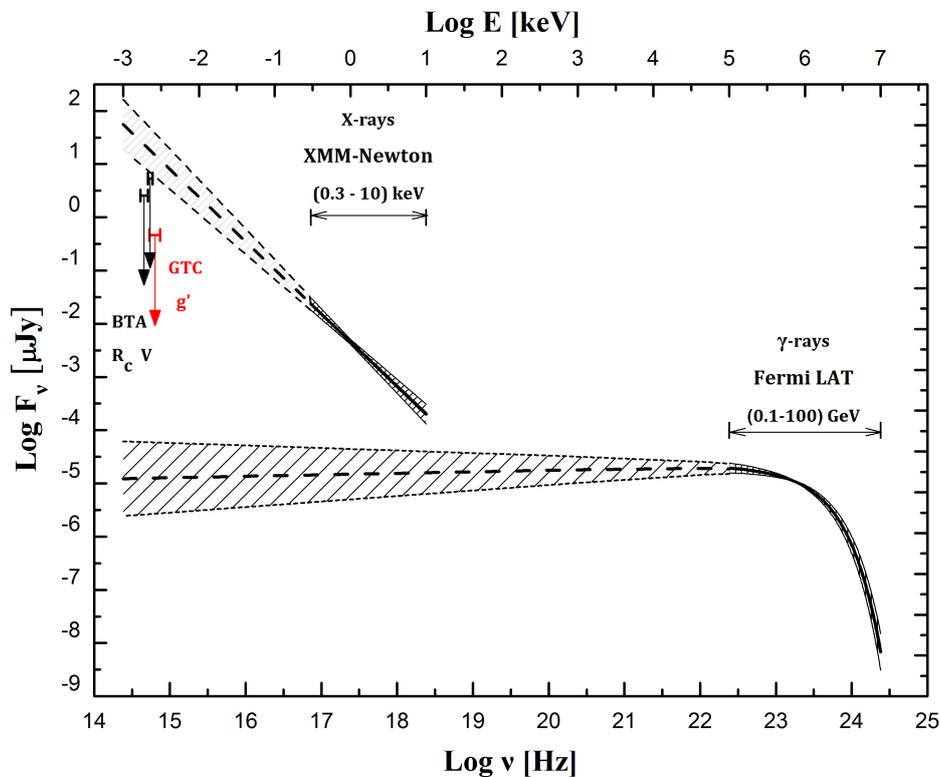


Figure 4. Unabsorbed spectrum of PSR J2055+2539. The instrument detection ranges are marked by horizontal bars. Solid lines indicate the best spectral fits of the XMM-Newton and *Fermi* LAT data, extrapolated toward the optical range with dashed lines. Shaded regions correspond to 1σ uncertainties of fitting parameters. Horizontal bars with arrows mark the 3σ detection limits according to the *GTC* (the red one) and *BTA* data (the black ones).

4. Conclusions

We conducted the deep, down to $g'_{lim} = 28$, optical observations of PSR J2055+2539 with the *GTC*. We performed the correction of the *Chandra* absolute astrometry using two reference stars, detected both in the optical and X-rays. This improvement resulted in the most precise pulsar position with the 1σ uncertainty of roughly $0''.2$. However, within the corresponding 3σ error ellipse there is no reliable counterpart of J2055 in the *GTC* image. The conservative detection

limit on the pulsar emission $g' = 26.6$. It is brighter than the limit stated above due to the presence of the nearby relatively bright star with $g' = 20.3$, located $0''.8$ from the pulsar. The multiwavelength spectrum including this upper limit confirms the spectral break between the optical and X-rays, that was suggested in [4]. Further optical searches for the pulsar require a high spatial resolution which can be provided using either ground-based telescopes equipped with adaptive optics or the *HST*.

Acknowledgments

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