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# Large Binocular Telescope observations of PSR J2043+2740\*

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## ABSTRACT

We present the results of deep optical imaging of the radio/ $\gamma$ -ray pulsar PSR J2043+2740, obtained with the Large Binocular Telescope (LBT). With a characteristic age of 1.2 Myr, PSR J2043+2740 is one of the oldest (non-recycled) pulsars detected in  $\gamma$ -rays, although with still a quite high rotational energy reservoir ( $\dot{E}_{\text{rot}} = 5.6 \times 10^{34} \text{ erg s}^{-1}$ ). The presumably close distance (a few hundred pc), suggested by the hydrogen column density ( $N_{\text{H}} \lesssim 3.6 \times 10^{20} \text{ cm}^{-2}$ ), would make it a viable target for deep optical observations, never attempted until now. We observed the pulsar with the Large Binocular Camera of the LBT. The only object ( $V = 25.44 \pm 0.05$ ) detected within  $\sim 3$  arcsec from the pulsar radio coordinates is unrelated to it. PSR J2043+2740 is, thus, undetected down to  $V \sim 26.6$  ( $3\sigma$ ), the deepest limit on its optical emission. We discuss the implications of this result on the pulsar emission properties.

**Key words:** stars: neutron – pulsars: individual.

## 1 INTRODUCTION

The launch of the *Fermi Gamma-ray Space Telescope* has spurred on the search for pulsars in  $\gamma$ -rays (Grenier & Harding 2015), yielding over 200<sup>1</sup> detections and triggering multiwavelength observations. While pulsars are common targets in the X-rays, they are very challenging targets in the optical and very few of them have been identified (see Mignani et al. 2016, and references therein). Here, we report on Large Binocular Telescope (LBT) observations of an isolated pulsar, PSR J2043+2740 (Taylor, Manchester & Lyne 1993), detected by both *AGILE* (Pellizzoni et al. 2009) and *Fermi* (Abdo et al. 2010; Noutsios et al. 2011). It was discovered as a radio pulsar (Ray et al. 1996) and later on as an X-ray source by *XMM-Newton* (Becker et al. 2004), although

X-ray pulsations have not yet been found. PSR J2043+2740 is one of the very few non-recycled pulsars older than 1 Myr detected in  $\gamma$ -rays, with a characteristic age  $\tau_c = 1.2$  Myr, inferred from the values of its spin period  $P_s = 0.096$  s and its derivative  $\dot{P}_s = 1.27 \times 10^{-15} \text{ s s}^{-1}$  (Ray et al. 1996). This also yields a rotational energy loss rate  $\dot{E}_{\text{rot}} = 5.6 \times 10^{34} \text{ erg s}^{-1}$  and a surface dipolar magnetic field  $B_s = 3.54 \times 10^{11} \text{ G}$ .<sup>2</sup> Although PSR J2043+2740 does not have a very large spin-down power compared to young ( $\sim 1$ – $10$  kyr) pulsars ( $\sim 10^{36}$ – $10^{38} \text{ erg s}^{-1}$ ), it is still a factor of 2 larger than that of middle aged  $\gamma$ -ray pulsars ( $\sim 0.1$ – $0.5$  Myr), such as Geminga, PSR B0656+14 and PSR B1055–52, all detected in the optical, thanks to their distances  $\lesssim 500$  pc (Abdo et al. 2013). The distance to PSR J2043+2740 is uncertain owing to the lack of a radio parallax measurement. The radio dispersion measure ( $\text{DM} = 21.0 \pm 0.1 \text{ pc cm}^{-3}$ ; Ray et al. 1996) gives a distance of  $1.8 \pm 0.3$  kpc from the NE2001 model of the Galactic-free electron density (Cordes & Lazio 2002). A slightly smaller distance (1.48 kpc) is inferred from the model of Yao, Manchester & Wang (2017). The hydrogen column density towards the pulsar obtained from the X-ray spectral fits ( $N_{\text{H}} \lesssim 3.6 \times 10^{20} \text{ cm}^{-2}$ ; Abdo et al. 2013) suggests a distance of a few hundred pc (He, Ng & Kaspi 2013), although these estimates depend on the model X-ray spectrum. Such a distance

\* The LBT is an international collaboration among institutions in the United States, Italy and Germany. LBT Corporation partners are: The University of Arizona on behalf of the Arizona university system; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, the Astrophysical Institute Potsdam and Heidelberg University; The Ohio State University, and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota and University of Virginia.

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<sup>1</sup> <https://confluence.slac.stanford.edu/display/GLAMCOG/>

<sup>2</sup> Derived from the magnetic dipole model, e.g. Kaspi & Kramer (2016).

would make PSR J2043+2740 a viable target for deep optical observations, never carried out until now, and might be compatible with the debated association (Noutsios et al. 2011) with the Cygnus Loop supernova remnant (SNR) at  $540_{-80}^{+100}$  pc (Blair, Sankrit & Raymond 2005).

The structure of this manuscript is as follows: observations and data reduction are described in Section 2, whereas the results are presented and discussed in Sections 3 and 4, respectively.

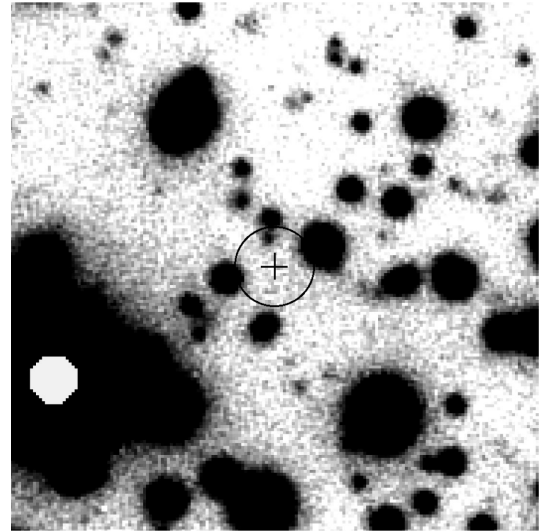
## 2 OBSERVATIONS AND DATA ANALYSIS

The PSR J2043+2740 observations were carried out on 2016 July 5, with the LBT at the Mount Graham International Observatory (Arizona, USA) and the Large Binocular Camera (LBC; Giallongo et al. 2008). The camera’s field of view is  $23 \text{ arcmin} \times 25 \text{ arcmin}$ , with a pixel scale of  $0.2255 \text{ arcsec}$ . The images were taken through the filters SDT-USpec, V-BESSEL and *i*-SLOAN, closely matching the Sloan filters *u* and *i* (Fukugita et al. 1996) and the Johnson *V* filter. For each filter, three sets of exposures were acquired with exposure times of 20, 60 and 120 s, for a total integration of 5887 s (USpec and *i*-SLOAN) and 5376 s (V-BESSEL). Sky conditions were non-photometric owing to the presence of cirri and the average seeing was around  $1.2 \text{ arcsec}$ . The target was observed with an average airmass around 1.01 and 1.09, and with a lunar illumination of  $\sim 1$  per cent. Images were reduced with the LBC data reduction pipeline, correcting raw science frames for bias, dark and flat-fields. A further low-order flat-field correction was obtained from the night sky flats to remove large-scale effects. We, then, corrected the images for geometrical distortions, applying a linear pixel scale resampling. Finally, we stacked all images taken with the same filter and used the master frames to compute the astrometric solution ( $\sim 0.1 \text{ arcsec rms}$ ).

Since the night was non-photometric, we performed the photometric calibration directly on the science frames by matching stars in public source catalogues. In particular, for the SDT-USpec filter we used a source list extracted from the *XMM-Newton* Serendipitous Ultra-violet Source Survey Catalogue version 3.0 (XMM-SUSS3<sup>3</sup>) (Page et al. 2012), built from observations with the *XMM-Newton* Optical Monitor (OM; Mason et al. 2001), whereas for both the V-BESSEL and *i*-SLOAN filters we used a source list from the American Association of Variable Stars Observers (AAVSO) Photometric All-Sky Survey<sup>4</sup> (APASS). All magnitudes are in the AB system (Oke 1974). For all filters, we computed object photometry with the DAOPHOT II software package (Stetson 1994) following a standard procedure for source detection, modelling of the image point spread function (PSF) and multiband source catalogue generation (see e.g. Testa et al. 2015). After accounting for photometric errors, the fit residuals turned out to be  $\sim 0.01 \text{ mag}$  in all filters, to which we must add the average absolute photometry accuracy of SUSS3 and APASS, which is  $\sim 0.05 \text{ mag}$ .

## 3 RESULTS

Fig. 1 shows a zoom of the *i*-band image centred around the pulsar position. The J2000 coordinates of PSR J2043+2740 used by Noutsios et al. (2011) are:  $\alpha = 20^{\text{h}}43^{\text{m}}43^{\text{s}}.52$ ;  $\delta = +27^{\circ}40'56''.06$  but with no quoted error. The ATNF pulsar catalogue (Manchester



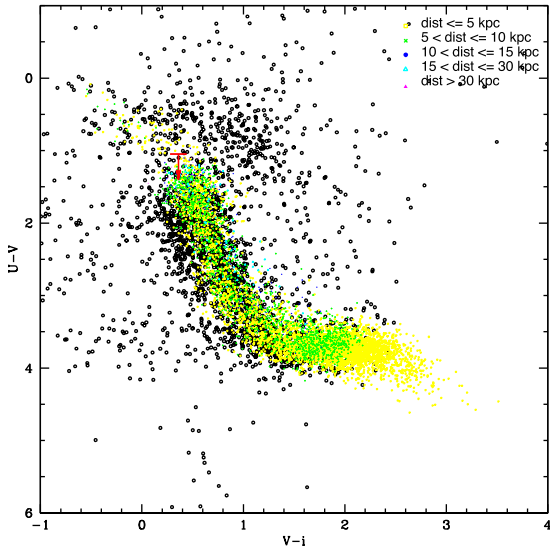
**Figure 1.** Zoom of the PSR J2043+2740 field ( $20 \text{ arcsec} \times 20 \text{ arcsec}$ ) obtained in the *i* band (5887 s) and centred on the pulsar position (cross). North is to the top, east to the left. The length of the cross arms ( $1 \text{ arcsec}$ ) is equal to the nominal uncertainty on the radio coordinates. The circle ( $3 \text{ arcsec}$  radius) indicates the search region assumed to account for the unknown pulsar proper motion.

et al. 2005) reports the same coordinates, with an uncertainty of  $0.1$  and  $1 \text{ arcsec}$  in right ascension and declination, respectively, at a reference epoch  $\text{MJD} = 49773$ . Owing to timing noise, no updated pulsar coordinates could be computed using the timing model of Kerr et al. (2015). PSR J2043+2740 has not been observed by *Chandra*, so that we cannot rely on an accurate, model-independent position. No proper motion has been measured for PSR J2043+2740. Therefore, to account for its unknown angular displacement between the epoch of the reference radio position and that of our LBT observations ( $\text{MJD} = 57574$ ), we looked for candidate counterparts within a conservative search region of  $3 \text{ arcsec}$  radius. This is three times as large as the formal radio position uncertainty and roughly equal to the angular displacement expected for a pulsar moving with an average transverse velocity of  $400 \text{ km s}^{-1}$  (Hobbs et al. 2005) at a distance as close as the Cygnus Loop SNR ( $540_{-80}^{+100}$  pc; Blair et al. 2005).

Only one object is detected within the search region ( $3 \text{ arcsec}$  radius) defined above (Fig. 1). The object is barely visible in the *V* band and not in the *U* band, whereas it is clearly detected in the *i* band. Its magnitudes have been computed following the same procedure as described in Section 2, and are  $V = 25.44 \pm 0.05$ ,  $i = 25.08 \pm 0.08$  and  $U > 26.5$  (AB). To investigate the characteristics of the object, we built a  $U-V$  versus  $V-i$  colour-colour diagram (CCD) of all objects within  $5 \text{ arcmin}$  from the pulsar position and compared its colours with respect to the main sequence (Fig. 2). Since the field stars are, presumably, at different distances with respect to the pulsar, the diagram is uncorrected for the reddening. The object’s colours are  $V-i = 0.36 \pm 0.09$ ,  $U-V > 1.06$  and are close to those of the main sequence. This means that it does not stand out for having peculiar colours, as one would expect for a pulsar, which is usually characterized by blue colours (e.g. Mignani & Caraveo 2001; Mignani, Pavlov & Kargaltsev 2010). We compared the observed CCD to a synthetic one computed with the Besançon Model of Stellar Population Synthesis to simulate the Galactic stellar population within a  $5 \text{ arcmin}$  radius around the direction of PSR J2043+2740. As shown in Fig. 2, the main sequence

<sup>3</sup> <https://www.cosmos.esa.int/web/xmm-newton/xsa>

<sup>4</sup> <http://www.aavso.org/apass>



**Figure 2.** Synthetic CCD for the Galactic stellar population (in colour for different distances) in the pulsar direction simulated with the Besançon model (Robin et al. 2004), superimposed to the observed one (black). The spread in the synthetic CCD is the effect of the distance-dependent reddening correction, applied by the model, and the simulated photometric error.

of the observed CCD is consistent with the model Galactic stellar population, supporting the conclusion that the object is a field star rather than the pulsar. Estimated  $3\sigma$ -level limiting magnitudes are 26.5, 26.6 and 26.2 in the  $U$ ,  $V$  and  $i$  bands, respectively, which we assume as upper limits on the pulsar fluxes.

#### 4 DISCUSSION

Our observations of PSR J2043+2740 are much deeper than those obtained by Beronya et al. (2015) with the BTA (Bolshoi Teleskop Alt-azimutalnyi) 6 m telescope, which only yielded a  $3\sigma$  limit of  $R \sim 21.7$  (Vega) on the pulsar flux. The pulsar is obviously too faint to have been detected in the *XMM-Newton* OM images (Becker et al. 2004), with  $3\sigma$  limits of  $B \approx 21.5$  and  $U \approx 20.9$  (Vega).

We checked whether our limits on the pulsar flux could help to prove or disprove the association with the Cygnus Loop SNR. In general, the non-thermal optical luminosity  $L_{\text{opt}}$  of rotation-powered pulsars scales with a power of the rotational energy loss rate (see e.g. Mignani et al. 2012) as  $L_{\text{opt}} \propto \dot{E}_{\text{rot}}^{1.70 \pm 0.03}$  ( $1\sigma$  statistical error). From this relation, we estimate a luminosity of  $\sim 3.16 \times 10^{27} \text{ erg s}^{-1}$  for PSR J2043+2740, corresponding to a magnitude  $V \sim 26.2\text{--}26.9$  at the distance of the Cygnus Loop SNR, after accounting for the interstellar reddening  $E(B - V) \lesssim 0.06$ , inferred from the  $N_{\text{H}}$  (Predehl & Schmitt 1995). Therefore, our detection limit ( $V \sim 26.6$ ) does not determine whether the pulsar is at the distance of the Cygnus Loop SNR, and their association remains uncertain. Pushing the limit on the pulsar brightness down to  $V \sim 28$  would imply a distance larger than  $\sim 1 \text{ kpc}$  for the same predicted optical luminosity and would disprove this association. Given the lack of a counter-evidence, we assume the pulsar DM-based distance (Yao et al. 2017) as a reference.

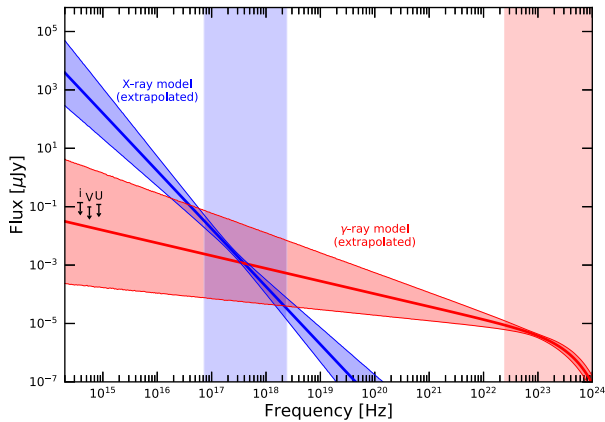
We compared our constraints on the optical emission of PSR J2043+2740 with the properties of other pulsars of comparable age identified in the optical (Table 1). Among them, PSR J2043+2740 lies somewhere in between the middle-aged pulsars, with the oldest being PSR B1055–52 ( $\tau_c \sim 0.5 \text{ Myr}$ ), and the oldish ones, such as PSR B1929+10 ( $\tau_c \sim 3 \text{ Myr}$ ). The

**Table 1.** A comparison between the optical properties of PSR J2043+2740 and the two pulsars closest in age detected in the optical.

	B1055–52	J2043+2740	B1929+10
$\tau_c$ (Myr)	0.5	1.2	3
$\dot{E}_{\text{rot}}$ ( $10^{34} \text{ erg s}^{-1}$ )	3.0	5.6	0.39
$L_{\text{opt}}$ ( $10^{27} \text{ erg s}^{-1}$ )	3.74	$\lesssim 22.0$	1.04
$\eta_{\text{opt}}$ ( $10^{-7}$ )	1.26	$\lesssim 3.93$	2.7
$F_{\text{opt}}/F_{\gamma}$ ( $10^{-6}$ )	0.88	$\lesssim 7.14$	$\gtrsim 31.1$
$F_{\text{opt}}/F_{\text{X}}$ ( $10^{-4}$ )	16.9	$\lesssim 5.57$	3.4

$V$ -band optical luminosity of PSR J2043+2740 is  $L_{\text{opt}} \lesssim 2.2 \times 10^{28} d_{1.48}^2 \text{ erg s}^{-1}$ , where  $d_{1.48}$  is its distance in units of 1.48 kpc (Yao et al. 2017). If one assumes that the  $V$ -band optical emission is entirely non-thermal and rotation powered, its emission efficiency would be  $\eta_{\text{opt}} \lesssim 3.93 \times 10^{-7} d_{1.48}^2$ . For a comparison, for a distance of 0.35 kpc (Mignani et al. 2010), the  $V$ -band optical luminosity of PSR B1055–52 would be  $3.74 \times 10^{27} \text{ erg s}^{-1}$  and its emission efficiency  $1.26 \times 10^{-7}$ . We note that the optical spectrum of PSR B1055–52 brings the contribution of both non-thermal emission from the magnetosphere and thermal emission from the neutron star surface and is the combination of a power law (PL) and a Rayleigh-Jeans (R-J; Mignani et al. 2010), as observed in other middle-aged pulsars. However, the contribution of the R-J in the  $V$  band is about an order of magnitude smaller than that of the PL, so that its  $V$ -band luminosity is essentially non-thermal. The  $\gamma$ -ray energy flux above 100 MeV for PSR J2043+2740 is  $F_{\gamma} = (1.18 \pm 0.12) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$  (Acero et al. 2015), whereas its unabsorbed non-thermal X-ray flux (0.3–10 keV) is  $F_{\text{X}} = 0.22_{-0.11}^{+0.03} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$  (Abdo et al. 2013), which gives an optical-to- $\gamma$ -ray flux ratio  $F_{\text{opt}}/F_{\gamma} \lesssim 7.14 \times 10^{-6}$  and an optical-to-X-ray flux ratio  $F_{\text{opt}}/F_{\text{X}} \lesssim 5.57 \times 10^{-4}$ , where the optical flux  $F_{\text{opt}}$  has been corrected for the extinction. For PSR B1055–52,  $F_{\gamma} = (2.90 \pm 0.03) \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$  and  $F_{\text{X}} = 1.51_{-0.13}^{+0.02} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$  (0.3–10 keV), yielding  $F_{\text{opt}}/F_{\gamma} \sim 0.88 \times 10^{-6}$  and  $F_{\text{opt}}/F_{\text{X}} \sim 16.9 \times 10^{-4}$ , whereas for PSR B1929+10 the  $V$ -band optical luminosity would be  $1.04 \times 10^{27} \text{ erg s}^{-1}$  for a 0.31 kpc distance (Verbiest et al. 2012) and its emission efficiency  $\sim 2.7 \times 10^{-7}$ . However, PSR B1929+10 has not been observed in the optical but in the near-UV (Mignani et al. 2002), where the spectrum is modelled by a PL with spectral index  $\alpha \sim 0.5$ . Therefore, its extrapolation to the optical gives uncertain predictions on the unabsorbed  $V$ -band flux, and it is not possible to determine whether it decouples into a PL plus an R-J, like in PSR B1055–52 (Mignani et al. 2010). In this case, both the non-thermal optical luminosity and emission efficiency would be overestimated. PSR B1929+10 has been detected in the X-rays with an unabsorbed non-thermal 0.3–10 keV flux  $F_{\text{X}} = 2.64_{-0.16}^{+0.12} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$  (Becker et al. 2006), but not in  $\gamma$ -rays down to  $2.9 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$  (Romani et al. 2011), yielding  $F_{\text{opt}}/F_{\text{X}} \sim 3.4 \times 10^{-4}$  and  $F_{\text{opt}}/F_{\gamma} \gtrsim 3.11 \times 10^{-5}$ .

The  $\gamma$ -ray spectrum of PSR J2043+2740 is described by a PL with an exponential cutoff, where photon index  $\Gamma_{\gamma} = 1.44 \pm 0.25$  and cutoff energy  $E_c = 1.34 \pm 0.37 \text{ GeV}$  (Acero et al. 2015). The *XMM-Newton* spectrum can be fitted by a PL with  $\Gamma_{\text{X}} = 2.98_{-0.29}^{+0.44}$  (Abdo et al. 2013). The addition of a blackbody component is compatible with the counting statistics, but an  $f$ -test (Bevington 1969) shows no improvement in the fit significance. We compared our optical flux measurements with the extrapolations of the high-energy spectra, after correcting for the reddening using the extinction coefficients of Fitzpatrick (1999). The spectral energy distribution



**Figure 3.** SED of PSR J2043+2740. The extinction-corrected optical flux upper limits are labelled with the band names. The blue and red lines are the extrapolation of the X- and  $\gamma$ -ray PL spectra, respectively (Abdo et al. 2013; Acero et al. 2015), with their  $1\sigma$  errors (dashed lines). The blue and red regions mark the range where the X- and  $\gamma$ -ray spectra were measured.

(SED) of PSR J2043+2740 is shown in Fig. 3. As seen in other cases, the extrapolations of the two PL spectra are not compatible with each other, implying a turnover in the  $\gamma$ -ray PL at low energies. This is also observed in, e.g. the middle-aged pulsar PSR B1055–52 (Mignani et al. 2010), although there is no apparent correlation between the presence of a turnover and the pulsar characteristic age. The optical flux upper limits are below the extrapolation of the assumed X-ray PL spectrum, but are not deep enough to rule out that the optical emission might be compatible with the  $\gamma$ -ray PL extrapolation. This could be a rare case where the  $\gamma$ -ray and optical spectra are related to each other.

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