Deep optical imaging of the $\gamma$-ray pulsar J1048–5832 with the VLT *

A. Danilenko$^1$, A. Kirichenko$^{1,2}$, J. Sollerman$^3$, Yu. Shibanov$^{1,2}$, and D. Zyuzin$^{1,2}$

1 Ioffe Physical Technical Institute, Politekhnnicheskaya 26, St. Petersburg, 194021, Russia
danila@astro.ioffe.ru, shib@astro.ioffe.ru
2 St. Petersburg State Polytechnical Univ., Politekhnnicheskaya 29, St. Petersburg, 195251, Russia
aida.taylor@gmail.com, da.zyuzin@gmail.com
3 The Oskar Klein Centre, Department of Astronomy, Stockholm University, AlbaNova, 106 91 Stockholm, Sweden

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ABSTRACT

Context. PSR J1048–5832 is a young radio-pulsar that was recently detected in $\gamma$-rays with Fermi, and also in X-rays with Chandra and XMM-Newton. It powers a compact pulsar wind nebula visible in X-rays and is in many ways similar to the Vela pulsar.

Aims. We present deep optical observations with the ESO Very Large Telescope to search for optical counterparts of the pulsar and its nebula and to explore their multi-wavelength emission properties.

Methods. The data were obtained in V and R bands and compared with archival data in other spectral domains.

Results. We do not detect the pulsar in the optical and derive informative upper limits of $R \geq 28^{\prime}\prime.1$ and $V \geq 28^{\prime}\prime.4$ for its brightness. Using a red-clump star method, we estimate an interstellar extinction towards the pulsar of $A_{V} \approx 2$ mag, which is consistent with the absorbing column density derived form X-rays. The respective distance agrees with the dispersion measure distance. We reanalyse the Chandra X-ray data and compare the dereddened upper limits with the unabsorbed X-ray spectrum of the pulsar. We find that regarding its optical-$\gamma$-ray spectral properties this $\gamma$-ray pulsar is not distinct from other pulsars detected in both ranges. However, like the Vela pulsar, it is very inefficient in the optical and X-rays. Among a dozen optical sources overlapping with the pulsar X-ray nebula we find one with $V \approx 26^{\prime}\prime.9$ and $R \approx 26^{\prime}\prime.3$, whose colour is slightly bluer then that of the field stars and consistent with the peculiar colours typical for pulsar nebula features. It positionally coincides with a relatively bright feature of the pulsar X-ray nebula, resembling the Crab wisp and located in $\sim 2^\circ$ from the pulsar. We suggest this source as a counterpart candidate to the feature.

Conclusions. Based on the substantial interstellar extinction towards the pulsar and its optical inefficiency, further optical studies should be carried out at longer wavelengths.

Key words. pulsars: general – SNRs, pulsars, pulsar wind nebulae, individual: PSR J1048–5832 – stars: neutron

1. Introduction

Rotation-powered pulsars are believed to be the most numerous of all $\gamma$-ray sources in the Galaxy. Nevertheless, only about ten pulsars were discovered in $\gamma$-rays until the launch of the Fermi Gamma-ray Space Telescope (Thompson 2008). The number of $\gamma$-ray pulsars has now become about ten times larger, including many which have not yet been identified in the radio range. The majority of the early known $\gamma$-ray pulsars are also identified in the optical and X-rays. This provides a unique possibility to compile multi-wavelength spectra and light curves for these objects for the study of the not yet clearly understood radiative mechanisms responsible for the pulsar emission. Only six such multi-wavelength objects are detected in the optical. Increasing the number of optically identified $\gamma$-ray pulsars is highly desirable and the Fermi discoveries open up a new window for that.

The first Fermi catalogue (Abdo et al. 2010) provided poor accuracy (several arc-minutes) of the source spatial localisation. Therefore only those new $\gamma$-ray pulsars whose coordinates were known with higher accuracy from radio and/or X-ray observations were suitable for optical counterparts searches. Here we present optical followup observations of one of the "radio-selected" Fermi-pulsars, PSR J1048–5832 (B1046–58), obtained with the ESO Very Large Telescope (VLT). This is a 124 ms Vela-like radio-pulsar with a characteristic age of 20.4 kyr and a spin-down luminosity of $2 \times 10^{36}$ erg s$^{-1}$, discovered in the radio by Johnston et al. (1992) and later in X-rays by Gonzalez et al. (2006). It was mentioned as a low significance $\gamma$-ray pulsar in the Third EGRET catalogue (Thompson 2008) but was confirmed with Fermi (Abdo et al. 2010). The dispersion measure (DM) of 129 pc cm$^{-3}$ implies a distance of 2.7 kpc. A faint, presumably tail-like pulsar wind nebula (PWN) was also detected around the pulsar in X-rays (Gonzalez et al. 2006).

We imaged the pulsar field in V and R bands. Mignani et al. (2011) reported their non-detection of an optical counterpart based on our V-band data only. Here we analyse the data in both bands and examine colours of optical sources located close to the pulsar and within its PWN extent. We confirm the non-detection in the V band and derive deep optical flux upper limits for the pulsar in both bands within its 1$\sigma$ position uncertainty in X-rays. The observations and data reduction are described in Sect. 2; our results are presented in Sect. 3 and discussed in Sect. 4.

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1 see https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars
2. Observations and data reduction

2.1. Observations

The pulsar field was imaged in the \( V_{\text{HIGH}} \) and \( R_{\text{SPECIAL}} \) bands with the FOCal Reducer and low dispersion Spectrograph (FORS2) at the VLT/UT1 (ANTU) during several service mode runs in 2010, and 2011 (see Table 1). The observations were performed with the Standard Resolution collimator providing a pixel size of \( 0.165 \) (2×2 binning) and field size of \( 6.8 \times 6.8 \). Sets of twelve- and ten-minute dithered exposures were obtained in the \( V \) and \( R \) bands, respectively. Three short, 15 sec, exposures were taken in the \( V \) band to minimise the number of saturated sources in the crowded pulsar field and were used for astrometry. The observing conditions were photometric during the runs, with seeing varying from \( 0.4 \) to \( 1'.0 \).

Standard data reduction, including bias subtraction, flat-fielding, cosmic-ray removal, and geometric distortion corrections, was performed making use of the IRAF and MIDAS tools. We then aligned and combined all individual frames in each of the bands, using a set of unsaturated stars. The alignment accuracy was \( \leq 0.1 \) of a pixel. The resulting mean seeing values were \( 0.63 \) and \( 0.64 \), and the integration times were 24 and 16.8 ks, for the combined \( V \) and \( R \) images, respectively.

2.2. Astrometric referencing

For astrometric referencing the shallow \( V \) band (Table 1) images were used. The positions of the astrometric standards from the USNO-B1 astrometric catalogue were used as a reference. To minimise uncertainties caused by overlapping stellar profiles in the crowded FOV, we selected only 15 isolated non-saturated stars. Their pixel coordinates were derived using the IRAF task \( \text{icmap} \) with an accuracy of \( \leq 0.007 \) pixels. The IRAF task \( \text{ccmap} \), allowing for the image scaling, shift, and rotation, was applied for the astrometric transformation of the image. Formal rms uncertainties of the astrometric fit were \( \Delta R A \leq 0.056 \) and \( \Delta Dec \leq 0.060 \), and the fit residuals were \( \leq 0.17 \), consistent with the nominal catalogue uncertainty of \( \approx 0.2 \). The combined deep \( V \) and \( R \) images were aligned to the short \( V \) reference frame with an accuracy of \( \leq 0.01 \). The resulting conservative 1\( \sigma \) referencing uncertainty for the combined images is \( \leq 0.2 \) in both \( RA \) and \( Dec \).

In order to compare optical and X-ray data, we also performed astrometric referencing of the best spatial resolution archival X-ray image of PSR J1048–5832 obtained with Chandra/ACIS. In the exposure-corrected ACIS-S3 chip image, where the pulsar is located, we found a dozen of point-like objects detected at \( \geq 3\sigma \) significance. We identified them with relatively bright optical reference objects from the USNO-B1 catalogue. Their image positions were defined using the CIAO \( \text{celldetect} \) tool with an accuracy of 0.5–3.0 of the ACIS pixel size (\( \approx 0.5 \)). Resulting formal rms uncertainties of the astrometric fit were \( \Delta R A \approx 0.424 \) and \( \Delta Dec \approx 0.22 \) with maximal residuals \( \leq 0.83 \) and \( \leq 0.54 \) in \( RA \) and \( Dec \), respectively. Combining the latter with the catalogue uncertainties, conservative 1\( \sigma \) X-ray image astrometric uncertainties are \( RA \leq 0.85 \) and \( Dec \leq 0.58 \). The shift between the raw and transformed images was insignificant, \( \sim 0.1 \).

Using \( \text{celldetect} \) we obtained the coordinates of the point-like pulsar X-ray counterpart, \( RA = 10:48:12.640 \) and \( Dec = -58:32:03.50 \), which are compatible with those reported by Gonzalez et al. (2006). The radii and positional angle of the 1\( \sigma \)-error ellipse of the source position are \( 0.335 \), \( 0.266 \), \( 168:663 \), respectively. Accounting for the image referencing uncertainties we estimate a conservative pulsar X-ray coordinate errors of \( 0.02 \) and \( 0.04 \) in \( RA \) and \( Dec \), respectively. Combining them with the optical referencing uncertainty we obtained the \( RA \) and \( Dec \) radii of the 1\( \sigma \)-error ellipse of the pulsar X-ray position on the optical images as \( 0.04 \) and \( 0.07 \), respectively.

2.3. Photometric calibration

The photometric calibration was carried out using standard stars from the photometric standard fields E3, NGC2298, NGC2437, and PG1525 (Stetson 2000) observed during the same nights as the target. We fixed the atmospheric extinction coefficients at their mean values adopted from the VLT home page: \( k_V \approx 0.14 \pm 0.01 \) and \( k_R \approx 0.09 \pm 0.01 \). The resulting magnitude zero-points for the combined images were \( V^{ZP} = 27.97 \pm 0.02 \) and \( R^{ZP} = 28.12 \pm 0.02 \), and colour-term coefficients in respective photometric equations are \( 0.15 \pm 0.03 \) and \( -0.01 \pm 0.03 \). The errors include the statistical measurement and extinction coefficient uncertainties, and marginal variations from night to night.

3. Results

3.1. Overview of the pulsar field

The \( \sim 6' \times 6' \) VLT FOV in the \( V \) band (left panel of Fig. 1) shows a complicated structure of the pulsar environment with a dark feature extended over the entire field. This is also seen in the \( R \) band and is fully consistent with a large scale structure in the H\( \alpha \) archival image (right panel of Fig. 1). The pulsar is near the middle of its eastern part. In the Spitzer archival images at 8 and 24 \( \mu m \) the dark part is filled with bright infrared emission, likely a signature of a warm dust, which is typical for star forming regions. Another neutron star, RRAT J1047–58 is located \( \sim 15' \) from the pulsar. Its distance is \( 2.33 \) kpc (Keane et al. 2011) is similar to that of J1048–5832. Both objects are only 1.5 northwards of the centre of the Carina complex, one of the largest H II regions in our Galaxy at a distance

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\[1\] For instrument details see http://www.eso.org/instruments/fors/

\[2\] see http://www.nofs.navy.mil/data/ichpix/

\[3\] see http://www.nofs.navy.mil/data/ichpix/

\[4\] Obs. ID 3842, date 2003.10.08, Exp. time 36 ks, PI V. Kaspi.

\[5\] see e.g. “A User’s Guide to Stellar CCD Photometry with IRAF” by P. Massey and L. Davis, http://iraf.net/irafdocs/

\[6\] Obtained with the CTIO 4-m telescope as a part of ChaMPlate survey (Grindlay et al. 2005).

\[7\] GLIMPSE project, PI S. Majewski.
of ~2.3 kpc (Smith 2006). It contains a neutron star, 2XMM J104608.7−594306 (Pires et al. 2012), and 6 potential neutron stars candidates (Townsley et al. 2011) showing past supernova activity. The complicated J1048−5832 environment is thus likely linked to the north edge of the Carina complex.

### 3.2. Examining the pulsar vicinity

In Fig. 2 we compare images of the pulsar vicinity in the VR bands and X-rays. The X-ray image is corrected for the ACIS exposure map and smoothed with a four pixel Gaussian kernel to better show the PWN shape. The X-ray position of the pulsar and its 1σ uncertainty are marked together with the radio interferometric (Stappers et al. 1999) and timing (Wang et al. 2000) ones. The X-ray position is in a good agreement with the interferometric one. This fact and our accurate X-ray astrometric

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**Fig. 1.** The field of PSR J1048−5832 obtained in the V band with the VLT (left), and in Hα with the CTIO (right). The dark horizontal lines in the VLT image are due to a gap between the two FORS2/CCD chips and dithered exposures. The box in the Hα image shows the VLT FOV. The red and black crosses are the positions of J1048−5832 and a nearby neutron star RRAT J1047−5841.

**Fig. 2.** The ~14″ × 14″ fragment of the VLT V (top-left) and R (top-middle) band optical, and Chandra 0.5–7 keV X-ray (left-bottom) images of the PSR J1048−5832 vicinity. The Chandra image is smoothed with a four pixel Gaussian kernel. Colour-bars show brightness scales in 1000 counts in the optical and in counts in X-rays. The cross marks the X-ray position of the pulsar. White-dashed, and black-dashed ellipses show its 1σ uncertainties in X-rays and two radio observations, respectively. Yellow contours in the R-band image are overlaid from the X-ray image to indicate the PWN structure. Optical sources overlapping with the error ellipses and X-ray PWN are labelled by numbers. Top-right: The observed colour-magnitude diagram of PSR J1048−5832 field stars. The stars labelled in the images are highlighted.
referring allowing us to use the X-ray position as a reliable reference point in searching for the pulsar counterpart. The timing position is shifted significantly and likely suffers from systematic errors. The contours of the brightest regions and the outer boundary of the X-ray PWN are overlaid on the R image.

We do not resolve any reliable optical source within the pulsar 1σ X-ray error ellipse, but there are several optical sources overlapping with the PWN and radio ellipses. They are labelled by numbers and can be considered as potential counterparts of the pulsar, if it has a high proper motion, or its PWN structures.

3.3. Photometry and colour-magnitude diagram

Pulsars and PWNe typically have peculiar colours as compared to stars. To investigate whether the marked sources are associated with the pulsar and/or its PWN we performed Point Spread Function (PSF) photometry using the psf and allstar tasks of the IRAF D AOPHOT package (Stetson 1987). We set the psf-radius at ten pixels, where the bright isolated unsaturated stars selected for the PSF-construction merged with the background. The fit-radius and aperture radius for the PSF stars and the preliminary aperture photometry of the other stars were 2.5 pixels, while the annulus/dannulus for local background extractions were 15/10 pixels. We made aperture corrections based on photometry of bright unsaturated isolated field stars. The derived parameters satisfying the following conditions: \( \chi^2 \leq 1.5 \); sharpness \( \leq 1 \); position differences in \( V \) and \( R \) bands \( \leq 0.7 \) pixel. These criteria were also fulfilled for the sources listed in Table 2. The resulting sample contains about 3000 stars. The objects with magnitudes \( \leq 20^m5 \) are saturated and not included. The sources from the pulsar vicinity are highlighted in the diagram and numbered as in the images. All of them, except possibly source 5, are well within the distribution formed by the majority of field stars. They are likely belong to the main-sequence branch and, thus, are unlikely to be associated with the pulsar.

Within the uncertainties the colour \( V − R = 0.6 \pm 0.3 \) of source 5 is compatible with the \( V − R \leq 0.7 \) typical for pulsar/PWN optical counterparts, which are usually detected as faint blue objects. For instance, \( V − R = 0.4 \) for the Crab pulsar (Percival et al. 1993) and 0.7 for its PWN knot (Sandberg & Sollerman 2004). An association with the point-like pulsar is, however, excluded due to the large offset, \( 1\farcs7 \pm 0\farcs7 \), from the pulsar X-ray position. At \( d = 2.7 \) kpc this would imply an unrealistically high pulsar transverse velocity of \( 3100 \pm 1300 \) km s\(^{-1} \) on the 7 yr time base between the Chandra and VLT observations. The absence of any significant shift on the 6 yr time base between the interferometric and X-ray positions excludes such a motion.

3.4. Possible counterpart of the PWN

In Fig. 3 we compare the non-smoothed X-ray image of the pulsar vicinity with that in the R band where background stars have been subtracted except for source 5. There is a 4-σ significance compact X-ray structure within the PWN about 2′ southwest of the pulsar. The structure is outside the pulsar PSF FWHM and contains \( 12–14 \) source counts within the yellow region constraining its boundaries. It is reminiscent of the wisps in the Crab PWN observed in the optical and X-rays. The structure is labelled as “wisp ?” and yields an apparent drop-like shape of the brightest region around the pulsar in the smoothed X-ray image of Fig. 2. It spatially coincides with source 5. This is underlined by the yellow X-ray region overlaid on the optical image and by the spatial brightness profiles along the major PWN axis (right panels of Fig. 3). The putative wisp can also be resolved in the X-ray profile published by Gonzalez et al. (2006), although it is less pronounced.

The number density of sources observed within the VLT FOV in the brightness range \( 26^{m}9 \leq V \leq 28^{m}4 \), consistent with the source 5 brightness, is \( \approx 0.008 \) objects arcsec\(^{-2} \). The respective confusion probability to find an unrelated point-like optical source within the 90% Chandra positional uncertainty ellipse of the putative wisp is \( \approx 2\% \) and it becomes considerably smaller, \( \approx 0.2\% \), if we additionally constrain the colour \( (V − R) \leq 0.9 \), as is the source 5 case.

There are no other reliable potential counterparts of the PWN in our star subtracted images. A 1.5σ R flux enhancement seen within the pulsar X-ray error ellipse may indicate the presence of a faint pulsar counterpart candidate, but is consistent with a background fluctuation and the pulsar upper limits derived above.

3.5. Re-examination of the X-ray spectra

It is useful to compare the pulsar optical upper limits with its X-ray spectral data. Gonzalez et al. (2006) reported a spectral analysis of available Chandra and XMM-Newton data but only for the combined emission of the pulsar-PWN system. To examine

| Star | \( V \) (mag) | \( R \) (mag) | \( \log P_V \) (µJy) | \( \log P_R \) (µJy) |
|------|--------------|--------------|-------------------|-------------------|
| 1    | 26.6(1)      | 25.22(6)     | −1.11(6)          | −0.61(2)          |
| 2    | 24.62(3)     | 23.36(2)     | −0.29(1)          | 0.134(7)          |
| 3    | 26.6(2)      | 24.88(8)     | −1.09(9)          | −0.47(3)          |
| 4    | 26.9(2)      | 25.68(8)     | −1.22(7)          | −0.79(3)          |
| 5    | 26.9(2)      | 26.3(2)      | −1.23(9)          | −1.06(7)          |
| 6(D) | 26.1(1)      | 24.67(4)     | −0.90(4)          | −0.38(2)          |
| 7(C) | 23.92(2)     | 22.77(1)     | −0.015(6)         | 0.368(4)          |
| 8    | 26.5(1)      | 25.22(6)     | −1.08(5)          | −0.61(2)          |
| 9    | 25.62(6)     | 24.31(4)     | −0.69(2)          | −0.24(2)          |
| 10   | 23.41(2)     | 22.24(2)     | 0.189(8)          | 0.585(8)          |
| psr  | \( \geq 28.4 \) | \( \geq 28.1 \) | \( \leq -1.81 \) | \( \leq -1.76 \) |
the X-ray spectrum of the pulsar itself we performed an independent analysis. We first reanalysed the pulsar+PWN spectrum using the data from both instruments and our results are fully consistent with the published ones. The spectrum is described by an absorbed power-law, whereas the blackbody model gives an unrealistically high neutron star temperature.

We then focused on the Chandra/ACIS data where the pulsar is spatially resolved from the PWN (Fig. 3). We used three apertures shown in Fig. 4 to extract the spectra of the pulsar, the wisp, and the PWN. Error-bars indicate typical brightness uncertainties. The non-smoothed Chandra image (top) and star-subtracted VLT image (bottom). Magenta contours are X-ray contours of the PWN from Fig. 2. The cross and dashed ellipse are the position of the pulsar and its 1σ uncertainty. The yellow contour marks a relatively bright X-ray structure of the PWN 2′′ southeast of the pulsar, presumably a Crab-like wisp. It spatially coincides with the optical source 5, as can also be seen from the spatial brightness profiles extracted from a slice along the PWN major axis (a white-dashed rectangular on both images) presented in the left panels, where vertical dotted lines indicate the X-ray positions of the pulsar and the wisp.

There is a noticeable increase of the absorbing column density \( N_H \) when we move from the point-like pulsar to the extended PWN. This increase is significant for the south-east tail, which overlaps with the optically dark region in Fig. 2 and, therefore, is most strongly absorbed also in X-rays. The pulsar and north-western part of the PWN are in a more transparent region and \( N_H \) is lower for the pulsar and has an intermediate value for the entire system. We therefore believe that the \( N_H \) derived from the 1.5″ aperture is more realistic for the pulsar than the factor of 2 higher value obtained from the analysis of the pulsar+PWN spectrum.

![Fig. 3. The non-smoothed Chandra image (top) and star-subtracted VLT image (bottom). Magenta contours are X-ray contours of the PWN from Fig. 2. The cross and dashed ellipse are the position of the pulsar and its 1σ uncertainty. The yellow contour marks a relatively bright X-ray structure of the PWN 2′′ southeast of the pulsar, presumably a Crab-like wisp. It spatially coincides with the optical source 5, as can also be seen from the spatial brightness profiles extracted from a slice along the PWN major axis (a white-dashed rectangular on both images) presented in the left panels, where vertical dotted lines indicate the X-ray positions of the pulsar and the wisp. Error-bars indicate typical brightness uncertainties.](image)

Table 3. The absorbing column density \( N_H \), photon index \( \Gamma \), and normalisation factor \( PL \) of absorbing power-laws describing the Chandra spectra (see Fig. 4 and text). Errors correspond to \( \Delta C = 1 \).

| \( N_H \) \( 10^{22} \text{ cm}^{-2} \) | \( \Gamma \) | \( PL_{\text{norm}} \) \( 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \) | \( C \) \( \text{ (nbins) } \) |
|---|---|---|---|
| pulser | 0.34 \( ^{+0.16} \) \( ^{-0.16} \) | 1.46 \( ^{+0.34} \) \( ^{-0.35} \) | 3.6 \( ^{+1.8} \) \( ^{-1.5} \) | 245 (649) |
| pulsar+PWN | 0.60 \( ^{+0.18} \) \( ^{-0.15} \) | 1.59 \( ^{+0.21} \) \( ^{-0.28} \) | 12.8 \( ^{+5.3} \) \( ^{-3.5} \) | 448 (649) |
| south-east tail of the PWN | 1.90 \( ^{+0.71} \) \( ^{-0.61} \) | 2.11 \( ^{+0.69} \) \( ^{-0.64} \) | 11.8 \( ^{+1.1} \) \( ^{-0.6} \) | 267 (649) |
3.6. The interstellar extinction

The next step is dereddening the optical data. $N_H$ values from Table 3 and a standard relation between $N_H$ and the extinction factor $A_V$ (Predehl & Schmitt 1995), yield $A_V$ of 3.4$^{+0.8}_{-1.0}$, 10.6$^{+4.0}_{-3.4}$ and 1.8$^{+0.9}_{-0.7}$ for the pulsar+PWN, PWN tail, and pulsar, respectively. The first value is nearly equal to the entire Galactic extinction of 3.6 mag along the pulsar line-of-sight (Schlegel et al. 1998). The second one is significantly larger, in agreement with the absence of any stars in the dark region overlapping with the tail. The pulsar itself is apparently less reddened. To verify that, we made independent $A_V$ estimates using a method based on the red-clump stars as standard candles, which provides an $A_V$—distance relation for a given position on the sky (see e.g. López-Corredoira et al. 2002).

We extracted stars located within 0.3° of the pulsar position from the 2MASS All-Sky Point Source Catalogue and created a colour-magnitude diagram, $K$ vs $J-K$. We found mean $J-K$ colours of the red-clump branch in several magnitude bins and transformed them to the $A_V$—distance relation, as has been done by Danilenko et al. (2012) for another γ-ray pulsar J1357−6429. At a large distance limit this relation (Fig. 5) is in agreement with the entire Galactic extinction in this direction. For the DM pulsar distance of 2.7 kpc (the vertical dashed line in Fig. 5) it suggests $A_V \approx 2$, which is consistent with the X-ray spectral fit (the horizontal solid line) and with a mean foreground $A_V \approx 1.7$ for the Carina complex (Hillier et al. 2001).

Within the dark regions discussed above $A_V$ is obviously larger (cf. Povich et al. 2011), but these have a negligible contribution to the derived relation dominated by more transparent regions, in one of which the pulsar is located.

We thus consider $A_V \approx 1.8$, $N_H \approx 3 \times 10^{21} \text{ cm}^{-2}$, and $d \approx 2.7$ kpc as the most appropriate values, and hereafter use them for compilation of multi-wavelength spectrum and luminosity estimates of PSR J1048−5832.

3.7. Multi-wavelength spectrum and luminosities

The unabsorbed multi-wavelength spectrum of the pulsar is shown in Fig. 6. Its X-ray part is obtained with $N_H$ frozen at the value of $3 \times 10^{21} \text{ cm}^{-2}$, and the optical data are dereddened with $A_V = 1.8$. Our upper limits show that the real optical fluxes of the pulsar cannot significantly exceed the extrapolation of its X-ray spectrum to the optical range. This is typical for non-thermal radiation from pulsars detected in the optical and X-rays, including the Crab (Sandberg & Sollerman 2009), Vela (Shibanov et al. 2003), some middle-aged (Shibanov et al. 2006), and old pulsars (Zharikov et al. 2004, Zavlin & Pavlov 2004).

Using our spectral fits, the pulsar X-ray luminosity in the 2–10 keV range at $d = 2.7$ kpc, $L_{2–10}$ $\approx 10^{31.3}$ erg s$^{-1}$, and the pulsar to pulsar+PWN X-ray luminosity ratio $\approx 0.46$ are very similar to those of $\approx 10^{31.2}$ erg s$^{-1}$ and 0.34, respectively, obtained for the Vela pulsar, which has a similar age and spin-down luminosity. Comparing this together with our constraints of optical luminosity $L_{OPT} \leq 10^{28.9}$ erg s$^{-1}$ and the efficiency of transformation of its spin-down luminosity $E$ to optical photons $L_{opt}/E \leq 10^{-7.4}$ with the data available for other pulsars detected in the optical and X-rays (Zharikov et al. 2004, Danilenko et al. 2012), we conclude that, as the Vela pulsar, PSR J1048−5832 is rather inefficient in the optical and X-rays (Fig. 7).
Fig. 7. Comparison of X-ray and V-band luminosities and efficiencies for pulsars of different characteristic age $\tau$ detected in both spectral domains. Different pulsars are marked by different symbols and PSR J1048–5832 is shown by the red star. Both dependencies of pulsar efficiencies with age demonstrate an efficiency minimum near the Vela age, and the Vela-like J1048–5832 naturally occupies a place near this minimum.

4. Discussion and conclusions

We did not detect PSR J1048–5832 in our deep optical images of the field, down to a visual magnitude of $\sim 28$. The pulsar is located in a complicated region linked to the northern edge of the Carina complex with high star formation (and supernova) activity (Fig. 1). The region is filled by clumpy clouds where the interstellar extinction and absorbing column density vary substantially even at a 10'' scale. This complicates the optical identification of the pulsar and its PWN. Nevertheless, the derived pulsar optical flux upper limits are quite informative.

First, our VLT observations and reanalysis of the X-ray data show (Fig. 6) that the optical fluxes of the pulsar do not exceed the extrapolation of its power law X-ray spectrum towards the optical range, which is compatible with multi-wavelength non-thermal spectra for other rotation powered pulsars.

Second, our results show that this Vela-like pulsar is very inefficient in the optical and X-rays, as is the Vela pulsar itself (Fig. 7). In combination with a significant interstellar extinction and absorbing column density, this precludes us to detect it in our deep observations at a level consistent with the optical efficiency of the Vela pulsar.

We did detect a faint optical source coinciding with a relatively bright compact feature of the pulsar X-ray PWN, presumably a wisp, located $\sim 2''$ from the pulsar (Fig. 3). The source colour $V - R \approx 0.6$ is consistent with colours typical for PWNe structures, suggesting that the source is an optical counterpart candidate to the X-ray feature. The poor X-ray count statistics precludes us to constrain the multi-wavelength spectrum of the source and its background nature cannot be excluded.

Any further optical studies of the pulsar have to be carried out at longer wavelengths, which are less affected by the interstellar extinction.

Recent progress in the multi-wavelength studies of Vela-like pulsars adds new evidence of their low efficiency in the optical and X-rays. This forms a puzzling minimum in the optical and X-ray efficiency relations vs pulsar age, while in $\gamma$-rays it appears to be absent (Abdo et al. 2010). Further studies will show whether this is a signature of some interesting changes in a neutron star magnetosphere and particle acceleration at the 10 kyr age, or just an incomplete sample effect, which disappear when more Vela-like pulsars will be detected in the optical and X-rays.

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Note added: After submission of this paper also Razzano et al. (2013, MNras, 428, 3636) appeared. It is based on our data and their conclusion that star 6 cannot be the optical counterpart to the pulsar is consistent with our results while their pulsar flux upper limits are less deeper.

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