THE VELA PULSAR AND ITS LIKELY COUNTER-JET IN THE $K_s$ BAND

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ABSTRACT

We report the first high spatial resolution near-infrared (near-IR) imaging of the Vela pulsar in the $K_s$ band obtained with the new adaptive optics system recently mounted on the Gemini-South telescope. For the first time, we have firmly detected the pulsar in this band with $K_s \approx 21.8$ mag, and have resolved in detail an extended feature barely detected previously in the immediate vicinity of the pulsar in the $J$, $H$ bands. The pulsar $K_s$ flux is fully consistent with the extension of the flat optical spectrum of the pulsar toward the IR and does not confirm the strong IR flux excess in the pulsar emission suggested earlier by the low spatial resolution data. The extended feature is about two times brighter than the pulsar and is likely associated with its X-ray counter-jet. It extends $\sim 2^\prime$ southward of the pulsar along the X-ray counter-jet and shows knot-like structures and a red spectrum.

Key words: infrared: stars – pulsars: individual (Vela pulsar) – stars: neutron

1. INTRODUCTION

After the young Crab and B0540−69 pulsars with visual magnitudes of 16.5 mag and 22.6 mag, the 11 kyr old Vela pulsar with a magnitude of 23.6 mag is the third brightest in the optical among all known isolated neutron stars (NSs). The relative brightness has allowed us to perform detailed optical studies including successful timing, spectral, and polarization observations. Similar to the Crab pulsar, Vela has an almost flat spectrum from the near-infrared (near-IR) to the ultraviolet (UV; Mignani et al. 2007). The similarity has been unexpectedly broken by recent Spitzer observations in the mid-IR, where the Vela pulsar has shown a strong flux excess over its optical–UV spectrum extension toward the IR (Danilenko et al. 2011). This is completely different from the Crab, whose mid-IR and optical–UV spectra are described by a single power law (Sandberg & Sollerman 2009). Similar excesses have been detected for only two magnetars, 4U 0142+61 and 1E 2259+586 (Wang et al. 2006; Kaplan et al. 2009), where they were interpreted as emission from hypothetical fall-back X-ray irradiated disks around those NSs. However, Vela is not a magnetar. It is an ordinary rotation-powered pulsar emitting from radio to gamma-rays and powering, like the Crab, a bright (in X-rays) torus-like pulsar wind nebula (PWN) with polar jets (Helfand et al. 2001). The fall-back disk survival around such an active pulsar with a strong relativistic particle wind appears to be problematic (see, e.g., Jones 2007). Two other possibilities have been suggested to explain the excess (Danilenko et al. 2011): a complicated distribution function of emitting particles in the NS magnetosphere or a possible contamination of the pulsar flux by an unresolved PWN structure. The first one looks very unusual, while the second is supported by the presence of a faint nebulosity $2^\prime$ away from the pulsar tentatively detected in the near-IR VLT/ISAAC $J$, and $H$ images (Shibanov et al. 2003). The images had a higher spatial resolution than the Spitzer ones. The nebulosity is projected onto the origin of the pulsar X-ray counter-jet and has a red color, which could, in principle, explain the mid-IR excess (Danilenko et al. 2011). To check that, one needs higher spatial resolution imaging in the near-IR.

The Vela pulsar has never been observed in the $K$ band. Motivated by this and by the excess problem, we have carried out high spatial resolution imaging of the Vela field in the $K_s$ band with the new generation of the adaptive optics (AO) system recently mounted on the Gemini-South telescope (Carrasco et al. 2012). The observations and data reduction are described in Section 2, and the results are presented in Section 3 and discussed in Section 4.

2. GEMINI-SOUTH DATA

2.1. Observations, Data Reduction, and Calibration

The Vela pulsar was observed on 2013 January 30 in the $K_s$ band with the Gemini Multi-Conjugate Adaptive Optics System (GeMS) and its near-IR imager, the Gemini South Adaptive Optics Imager (GSAOI), mounted on the Gemini-South telescope. The observations were carried out in the service mode during the GeMS + GSAOI System Verification science program. The GSAOI science array is a $2 \times 2$ mosaic of four Rockwell HAWAII-2RG detectors forming a $4080 \times 4080$ pixel focal plane with a field of view of $85^\prime \times 85^\prime$ and a pixel scale of $0.02$. Each detector also contains a programmable On-Detector Guide Window (ODGW), which can provide tip/tilt information for a combination of up to four natural guide stars in GeMS. Three natural optical guide stars, NOMAD 0448-0138807 ($R \sim 15.6$ mag), 0448-0138766 (14.2 mag), and 0448-0138794 (14.3 mag), were used for the CANOPUS tip/tilt wave front sensor, which is the AO bench of GeMS. The latter star was also the ODGW IR guide star. The pulsar was exposed on chip 1 of the GSAOI array and we focus below on the data obtained from this chip. The observing conditions were photometric with seeing $\lesssim 0.55^\prime$.

We have obtained 19 dithered 100 s science exposures with $\sim 10^\prime$ offsets at an airmass of $\sim 1.04$. Gemini GeMS + GSAOI twilight flat fields were taken and used to create a master flat-field frame. Data reduction, linearity correction, sky...

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subtraction, flat-fielding, and bad pixel correction were performed using the IRAF\_gemi\_gsaoi tool. The effective mean seeing, defined as the FWHM of a stellar profile, on the chip 1 AO-corrected frames was in the range of 0'07–0'09, depending on the individual exposure and the source position on the frame. The best seeing concentrated within an ~0'3 region around the pulsar, in accordance with expectations for our AO observational setups. Differences in instrumental magnitudes of several field stars around the pulsar in different exposures were less than 1%. The reduced frames were aligned to a single reference frame of the best image quality and summed.\footnote{Final image located on http://www.ioffe.ru/astro/NSG/obs/index.html} The resulting effective mean seeing and integration time were 0'085 and 1900 s, respectively. The magnitude zero point of $C_{K_s} = 25.53(4) \text{mag}$ (instrumental fluxes in ADUs) for chip 1 was derived based on the photometric standards (9132, 9136, 9144, and 9146) from Persson et al. (1998) obtained on the same night. The atmospheric extinction of 0.065 mag in $K_s$ was taken from the GSAOI Web site.

### 2.2. Astrometry

We have performed the relative astrometry of the resulting $K_s$-band image using the VLT/ISAAC $J$-band image obtained 12 years ago by Shibanov et al. (2003) as a reference frame. Nine unsaturated isolated stars located in the pulsar vicinity were selected as the reference points and used in the IRAF geomap/ccmap tools to obtain the plate solutions. Formal rms uncertainties of the astrometric fit were $\lesssim 0'014$ with maximum residuals of $\lesssim 0'032$ for both coordinates. Taking into account the uncertainties of the reference star positions, which were $\lesssim 8 \text{mas}$ and $\lesssim 0.2 \text{mas}$ for the Very Large Telescope (VLT) and Gemini images, respectively, a conservative 1σ referencing uncertainty of the Gemini image with respect to the VLT images is $\lesssim 0'02$. Adopting the VLT absolute astrometric image referencing from Shibanov et al. (2003), the absolute astrometric uncertainty of the Gemini $K_s$-band image is $\approx 0'21$.

### 3. RESULTS

#### 3.1. Identification of the Pulsar and a Likely Counterpart of its Counter-jet

A fragment of the resulting $K_s$ image demonstrating the Vela pulsar vicinity is shown in the right panel of Figure 1. It is compared with a similar fragment obtained in the $H$ band with the VLT/ISAAC by Shibanov et al. (2003; left panel). We consider a point-like object marked by ‘+’ and detected in $K_s$ at $\sim 2\sigma$ significance as the Vela pulsar counterpart candidate. In the $K_s$ image, there is also an extended feature adjacent to the counterpart candidate from the south. This feature is also barely resolved in the $H$ band, which means that it is not an artifact.

The position of the suggested pulsar counterpart in the $K_s$ image is shifted by $0'068 \pm 0'05$ with respect to the pulsar position at the epoch of the VLT observations (2001). The shift implies a proper motion $\mu = 56 \pm 4 \text{mas yr}^{-1}$ with positional angle P.A. = 296°/4°, which is consistent with the pulsar proper motion $\mu = 58 \pm 0.1 \text{mas yr}^{-1}$ and P.A. = 301°/1° based on radio observations (Dodson et al. 2003). This is strong evidence that the point-like object detected in the $K_s$ image is the pulsar. No other point-like object in the pulsar vicinity demonstrates any significant proper motion.

The extended feature was named “counter-jet?” by Shibanov et al. (2003), assuming its possible association with the counter-jet of the Vela-torus-like X-ray PWN. The Gemini AO observations confirm this structure with a higher significance and reveal important details of its morphology. It extends southward from the pulsar by about $2''$ along the X-ray counter-jet axis with P.A. $\approx 130°$ (Helfand et al. 2001) marked by the dashed line in the right panel of Figure 1. This supports the association of the extended feature with the Vela X-ray counter-jet. In X-rays...
the counter-jet extends to a much larger distance up to 1′. In the near-IR it is likely that we see only its origin near the pulsar. The $K_s$-band counter-jet demonstrates a non-uniform morphology with several knots. The brightest knot is in the center of the feature. It is marked in Figure 1 and is reminiscent of the knot structure 0′6 away from the Crab pulsar, which is also projected onto the counter-jet origin of the Crab PWN (Hester et al. 1995). The Vela IR counter-jet is not detected in the optical range with the *Hubble Space Telescope* (HST; Shibanov et al. 2003), whose spatial resolution is comparable to that of Gemini/GSAOI. This implies that it has a very red spectrum. Also, it becomes evident that the putative counter-jet and the pulsar cannot be resolved from each other in the significantly lower spatial resolution *Spitzer* mid-IR images analyzed by Danilenko et al. (2011).

In the Gemini image we do not find any other extended structure that could be identified with other parts of the Vela PWN. In particular, we do not see the inner arc whose marginal detection in $J_α$ was discussed by Shibanov et al. (2003). In addition to the o1–o3 point-like objects from the pulsar neighborhood considered earlier (Shibanov et al. 2003; Danilenko et al. 2011), we find a red point-like source “o4” detected east of the pulsar at ~3σ confidence only in the $K_s$ image. It is significantly fainter than the pulsar and partially overlapped with it at the VLT observation epoch.

### 3.2. Photometry

For stellar-like object photometry, we used a circular aperture with a four pixel radius, comparable to the effective seeing of the $K_s$ image. The correction for finite aperture, derived from the point spread function (PSF) of bright stars located close to the pulsar, is $δm = 0.64(2)$. In this case, uncertainties include the PSF variation over the selected image section. For the counter-jet we used a polygon aperture shown in Figure 1, although the final results depend weakly on the specific aperture shape and background region parameters.

We have also remeasured the spatially integrated brightnesses of the counter-jet in the $J_α$ and $H$ bands. The photometry was performed on the VLT/ISAAC pulsar subtracted images (Shibanov et al. 2003; Figure 1). Our results differ significantly from those presented by Danilenko et al. (2011). The reason is that the authors used mean surface brightnesses from Shibanov et al. (2003), which were accidentally overestimated by 1.94 mag arcsec$^{-2}$ in both bands. After this correction the fluxes from Shibanov et al. (2003) are consistent with ours. All measured fluxes were de-reddened using $E_{B-V} = 0.055(5)$ and $R_V = 3.1$ (Shibanov et al. 2003). The results are summarized in Table 1.

For completeness, $K_s$ magnitudes of the o1, o2, o3, and o4 field objects are 22.48(8) mag, 20.53(4) mag, 18.77(4) mag, and 23.2(2) mag, respectively. The derived 3σ detection limit for a point-like object for a 0′.3 aperture (corresponding to ~90% of a point-like source flux) centered at some position in the pulsar vicinity free from any sources is 23.6 mag.

### 3.3. Spectra of the Vela Pulsar and Its “Counter-jet”

Using our photometry results, in Figure 2 we show an upgrade of the IR–UV spectra of the pulsar and its likely counter-jet feature compiled recently by Danilenko et al. (2011). One sees that the $K_s$ flux of the pulsar agrees well with the extrapolation of its flat power-law UV–optical spectrum toward the longer wavelengths. This makes the Vela pulsar spectral energy distribution (SED) similar to that of the younger Crab (Sandberg & Sollerman 2009).

At the same time, the counter-jet spatially integrated $K_s$ flux (shown by the red symbols in Figure 2) is about twice as high as the pulsar flux. The counter-jet $J_αH\ K_s$ fluxes demonstrate a very steep power-law SED with a spectral index of about three. The *Spitzer* fluxes are compatible with the long wavelength extrapolation of this SED, suggesting a common nature of the near-IR and mid-IR emission. We have checked that the essentially non-thermal, likely synchrotron, spectrum of the counter-jet is different from blackbody-like SEDs of the nearby stellar objects o1, o2, and o3. This means that the extended feature can hardly be just a combination of faint blended stars.

### Table 1

| Waveband | Observed | Dereddened |
|----------|----------|------------|
|          | $F_H$ (μJy) | $F_Ks$ (μJy) | $F_H$ (μJy) | $F_Ks$ (μJy) |
| $J_α$    | 18.48(22) | 1.06(9) | 18.48(22) | 1.06(9) |
| $H$      | $\geq 16.84$ | $\leq 1.52$ | $\geq 16.84$ | $\leq 1.52$ |
| $5.8\ μm$ | 16.38(27) | 1.51(11) | 16.38(27) | 1.51(11) |
| $8.0\ μm$ | $\geq 15.58$ | $\leq 1.70$ | $\geq 15.58$ | $\leq 1.70$ |

Notes.

a Numbers in brackets are 1σ uncertainties referring to the last significant digits quoted.
b $J_α$ and $H$-band data are from Shibanov et al. (2003).
c Mid-IR data are from Danilenko et al. (2011).

d 3σ detection limits for a 0′.3 aperture.

e $\delta m = 0.64(2)$. In this case, uncertainties include the PSF variation over the selected image section.
4. DISCUSSION

The Gemini-South ground-based observations with the new generation of the AO system have provided us with superb image quality comparable to that of the HST. This allowed us to firmly detect, for the first time, the Vela pulsar in the $K_s$ band. The measured pulsar flux is consistent with the extrapolation of the pulsar optical–UV spectrum toward the IR, which shows that the spectrum remains flat in this range and does not demonstrate any excess suggested earlier by the lower spatial resolution IR data. The AO observations also enabled us to confirm and resolve the feature extended immediately behind the pulsar. The elongation of the extended feature in the direction of the X-ray counter-jet and in the opposite direction of the pulsar proper motion suggests that it can be associated with the X-ray counter-jet. This is supported by the compact and relatively bright knot-like structure within the feature (Figure 1), which is reminiscent of the well known optical–near-IR knot within the south–east jet of the Crab pulsar.

The likely non-thermal spectrum of the Vela IR counter-jet is also similar to the spectrum of the Crab knot, which follows the power law with a spectral index of 1 and is responsible for an apparent excess of the Crab-pulsar mid-IR fluxes observed with Spitzer (Sandberg & Sollerman 2009). The spectrum of the Vela counter-jet is even steeper, resulting in a much stronger apparent excess of the Vela flux in the mid-IR. Our data practically rule out alternative interpretations of the mid-IR excess discussed by Danilenko et al. (2011), such as the fall-back disk or the complicated emitting particle distribution function in the pulsar magnetosphere. The Vela counter-jet spectrum is also consistent with the typically red spatially integrated optical–IR spectra of PWNe (Zharikov et al. 2013).

The Crab knot (Sandberg & Sollerman 2009) and Vela jets (Pavlov et al. 2001) are known to demonstrate a high temporal variability even on a week scale. The current data do not allow one to infer whether the Vela IR counter-jet is variable and moves together with the pulsar. Detection of such variability would thus serve as strong evidence for its PWN nature. This can also help to discard possible alternative interpretations, such as a Vela supernova remnant filament or a background galaxy at a cosmological distance. Some marginal evidence of the feature variability has been reported by Shibanov et al. (2003) based on the VLT near-IR observations. Forthcoming VLT/NACO and Spitzer data will hopefully find out whether the detected feature is variable, and clarify its spectrum and real nature. Observations at longer wavelengths are important to confirm the power-law spectrum of the feature. To detect other parts of the Vela PWN, deeper near-IR observations are necessary.

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Facility: Gemini:South

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