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On Dynamics and Spectra of Fine Spatial Structures in the Vela Pulsar Wind Nebula

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Abstract. Evolution of X-ray surface brightness and spectra of fine spatial structures in the Vela pulsar wind nebula (PWN) are studied. Variability of morphology and the spectrum of a small-scale structure at the base of the southern jet of the nebula – a bright transverse *bar* is investigated for the first time. The size of the bar located within $4''$–$5''$ from the Vela pulsar is $\sim 4.5'' \times 1.5''$. It is shown that brightness, shapes, and positions of the *bar* and the southern jet base vary on the timescale of 1–2 weeks, the *bar* can disappear and emerge again within 10 days. The power-law photon index of the jet base is much harder than that of the bar, 1.20 ± 0.12 vs 1.65 ± 0.15. The latter index is close to 1.6, a typical value for synchrotron emission of electrons accelerated at an ultrarelativistic shock. We speculate that bright blobs seen on both sides of the southern jet base may have the same nature as the bright blobs in the Crab PWN, which are believed to mark the position of the termination shock of the pulsar wind.

1. Introduction

Pulsar wind nebulae (PWNe) are bubbles of relativistic magnetized plasma blown out by pulsars, rotating magnetized neutron stars. The nebulae are fed by the $e^{\pm}$-winds of the pulsars and by their rotational energy. They appear as extended areas of bright emission (mostly, of synchrotron origin) around pulsars and form through the interaction of the pulsar wind (PW) with the surrounding medium (a supernova remnant, or the interstellar medium). PWNe show power-law spectra from radio-waves to gamma-rays and are thought to be powerful particle accelerators.

The distance of the Vela PWN is about 290 pc. It is energized by the relatively young (11 kyr) pulsar PSR B0833-45. X-ray observations of the nebula with the Chandra X-ray Observatory have revealed several bright and variable structures the most prominent being the two arcs and two extended jets with bright bases [9, 10]. Observations with Chandra allow one to resolve extended X-ray features of arcsecond scale.

2. Observations and data analysis

To study the dynamics of small scale X-ray structures of the Vela PWN we have analyzed the data of 11 observations performed with Chandra/ACIS in 2009-2010, each of 40 kiloseconds long (http://cxc.harvard.edu/cda; obs. ID 10132–10139, 12073–12075). We used standard routines from CIAO v.4.9 and XSpec v.12.9.1 to reprocess and analyse the data.

X-ray maps of the PWN in the 0.5–8 keV band were made for each observation. Their summed image is shown in Fig. 1. Following previous studies [10, 8] we chose for analysis several emitting structures rendered in Fig. 2: the wings of the outer (1a, 1b) and inner (2a, 2b) arcs, the central bright spot on the outer arc (3), the bases of northern (4) and southern (5) jets and a thin transverse bar (6) at the beginning of the southern jet's base. The position of the PSR is marked on the maps by a cross. The binning and smoothing parameters applied to produce the images are given in the Appendix (table 1).

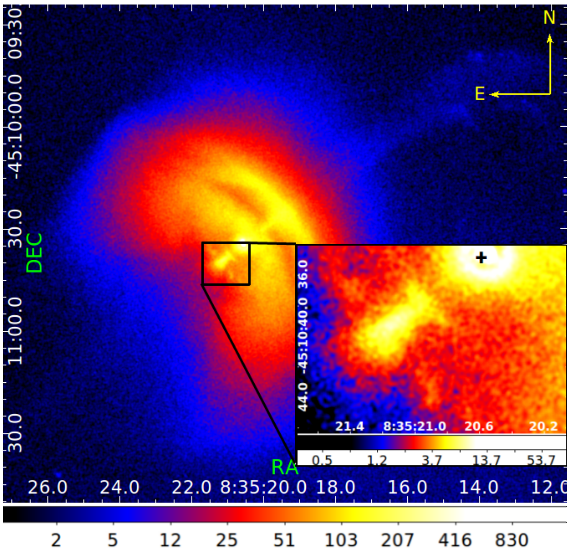

Figure 1. X-ray summed map of the Vela PWN in 0.5-8.0 keV range.

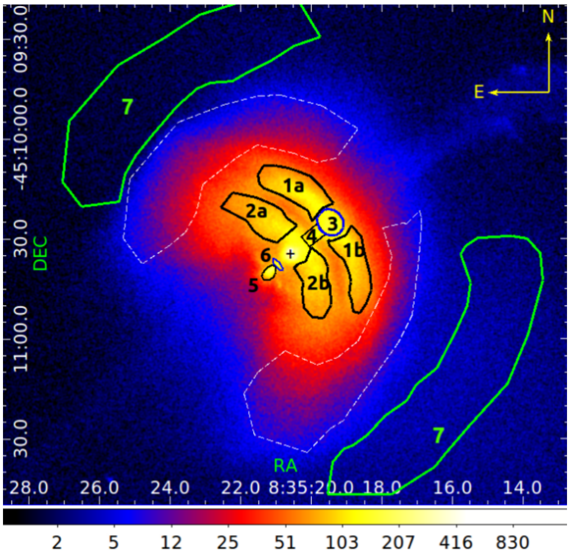

Figure 2. Structures of the Vela PWN selected for the analysis.

2.1. Morphology

The position of the PW termination shock (TS) in the Vela nebula is unknown. In the well studied Crab PWN the TS appears on the X-ray map as a bright ring (an ellipse in the sky plane projection), whose distant (SE) part consists of several blobs marked in Fig. 3 by letters A – D (notice the inverted color map). Similar blobs emerge on the X-ray maps of the Vela PWN on both sides of the southern jet's base. The structures are highly variable (alike Crab's blobs) and therefore look blurred on the summed image in Fig. 4, in contrast with individual images, like that shown in Fig. 5 for observation 10132. If the nature of these blobs is the same as in Crab, they might as well reveal the position of the TS.

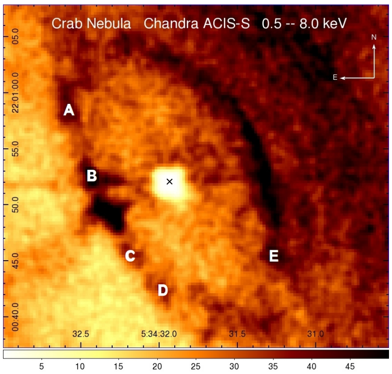

Figure 3. X-ray image of the Crab PWN[7]. The dark ring is thought to represent the pulsar wind TS with apparent bright blobs some of which are marked by capital letters.

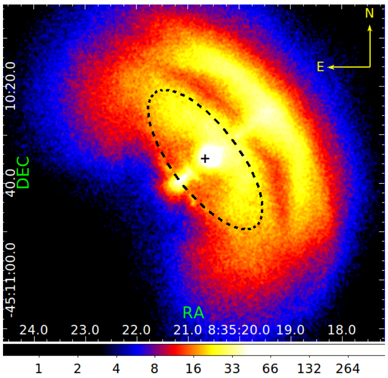

Figure 4. A possible geometry of the TS in the Vela PWN shown by the dashed ellipse. The SE edge of the ellipse outlines the bright blobs visible in the image of Fig. 5

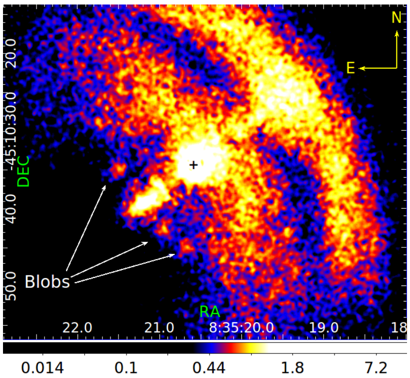

Figure 5. An X-ray image of the Vela PWN (obs. ID 10132). The bright blobs in the vicinity of the base of the SE jet are indicated by arrows.

Much longer exposures are needed to test this suggestion, due to the faintest spatial extent of the blobs and their fast variability. Such a hypothesis seems non-controversial at least geometrically: in Fig. 4 we inscribe into the Vela's X-ray map a TS ring whose distant (SE) edge touches the blobs, the nearest (NW) edge does not go beyond the diffuse emission of the inner arc, with the pulsar at the center and with the minor axis matching the PWN's symmetry axis.

2.2. The spectral and brightness variability of the prominent PWN structures

Using 11 observations of the Vela PWN we studied the spectral and surface brightness variability of its prominent structures in the 0.5–8 keV range. The emission of the PWN is mostly of synchrotron origin, so we have fitted the spectra with a power-law model corrected for the absorption of the X-rays in the interstellar medium [11]:

$$I(E) = A\left(\frac{E}{1\ keV}\right)^{-\Gamma}\exp\Big(-\sigma(E)\,N_{\mathrm{H}}\Big)\,. \tag{1}$$

The hydrogen column density N_{H} was fixed at $3.2{\cdot}10^{20}$ cm^{-2} as determined from the observation of the Vela pulsar with the Chandra LETG spectrometer [9]. The normalization A and the photon index Γ were determined as best-fit parameters. The area “7” in Fig. 2 was taken as the background for the spectral analysis (see comments in the Appendix).

Because of relatively large statistical errors the variations and correlations of photon indices with surface brightness cannot be traced with confidence, see Fig. 6, 7. One can discuss only the relative hardness of the spectra. If the X-rays emitting $e^{\pm}$ in PWNe would be accelerated at the wind TS only, then one would expect the spectra to have typical $\Gamma \sim 1.5$–1.6. However, if $e^{\pm}$ are pre-accelerated at the TS and are further accelerated in converging flows (see comments in the Appendix), they will acquire even harder spectra $\Gamma \sim 1$ [1].

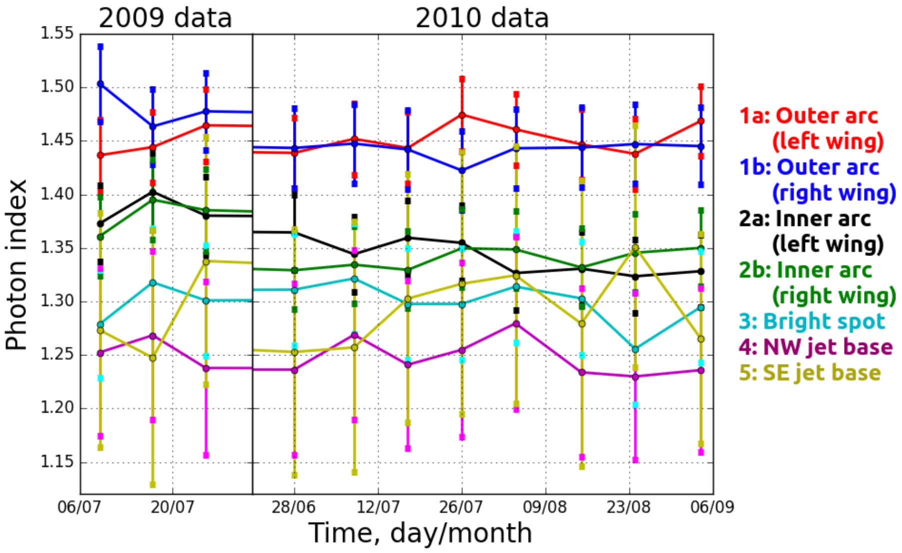

Figure 6. Evolution of 0.5–8.0 keV photon indices of the X-ray structures in the Vela PWN. The black vertical line indicates the 11 months gap between observations of 2009 and 2010. The error bars show 3σ errors.

Indeed, the photon indices we obtained ($\sim 1.2 - 1.5$) are substantially harder, in good agreement with the indices derived by [10, 5, 6]. The softest emission with $\Gamma \sim 1.5$ comes from the *outer arc* and its index is indeed close to that predicted for the emission of the electrons accelerated by Fermi mechanism at the TS of the relativistic pulsar wind. The emission of the other nebular structures is harder: $\Gamma \sim 1.3$–1.4 for the *inner arc* and ~ 1.2–1.3 for the *jets' bases* and the *bright spot* on the *outer arc*.

The energy fluxes (erg$\cdot$cm$^{-2}\cdot$s^{-1}) were determined from spectral fits and divided by the areas of the studied regions. No significant evolution of surface brightness of individual structures is observed, except the PWN *arcs* which swapped their relative brightness in the 11 months gap between the observations of 2009 and 2010; the right wing of the *inner arc* also got brighter by $\sim 15\%$.

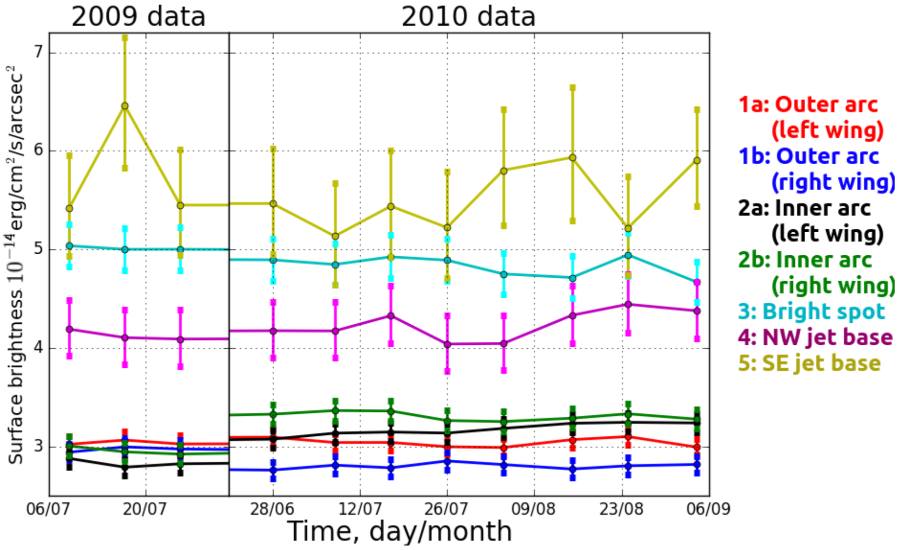

Figure 7. Evolution of unabsorbed 0.5–8.0 keV surface brightness (in units: 10^{-14} erg$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$arcsec^{-2}) of bright structures of the Vela PWN. The black vertical line separates observations of 2009 and 2010. The error bars show 3σ errors.

2.3. The Dynamics and Spectra of the Fine PWN Structures

For the first time we studied the dynamics and spectra of the immediate vicinity of the Vela pulsar. In the inset of Fig. 1 the region with the *base* of the southern jet and the *bar* is enlarged. Both structures are unstable and change their shape, brightness, and orientation in ~ 10 days. The *bar* can disappear and form again, as shown in Fig. 8. For example, in the image no. 10137 it is apparent, while in the image no. 10136 taken 9 days earlier it is almost indistinguishable. The *base* of southern jet seems to "wiggle": its inclination to the symmetry axis is slightly different in 2009 and 2010 observations. In some of 2010 observations the *base* seems curved a little.

The *bar* spectrum is obtained by fitting the combined data of 10 observations (obs. ID 10132–12074; 12075 was not used because the *bar* is absent on it). The angular size of the *bar* is $\sim 4.5'' \times 1.5''$, so it spans about 3×9 pixels of the ACIS detector. Therefore, statistics of the individual observations, i.e., the number of X-ray photons collected in this small area was subject to substantial uncertainties. From ~ 600 to 1000 counts were collected in the *bar* during the individual exposures. To compare, we obtained a combined spectrum for the southern jet *base*.

As mentioned above, the choice of background regions for the spectral analysis is not obvious because of the highly structured morphology of the nebula and the large mean free path of the X-ray emitting particles. We tried two different backgrounds shown in Fig. 9. With background I we got $\Gamma = 1.64^{+0.14}_{-0.13}$ (the errors here and below at the 3σ level) for the *bar* and $\Gamma = 1.14 \pm 0.06$ for the *jet base*. With background II we obtained $\Gamma = 1.60^{+0.08}_{-0.07}$ and $\Gamma = 1.25 \pm 0.04$, respectively. The fit qualities are given in the Appendix (Table 2). The estimates consistent with both

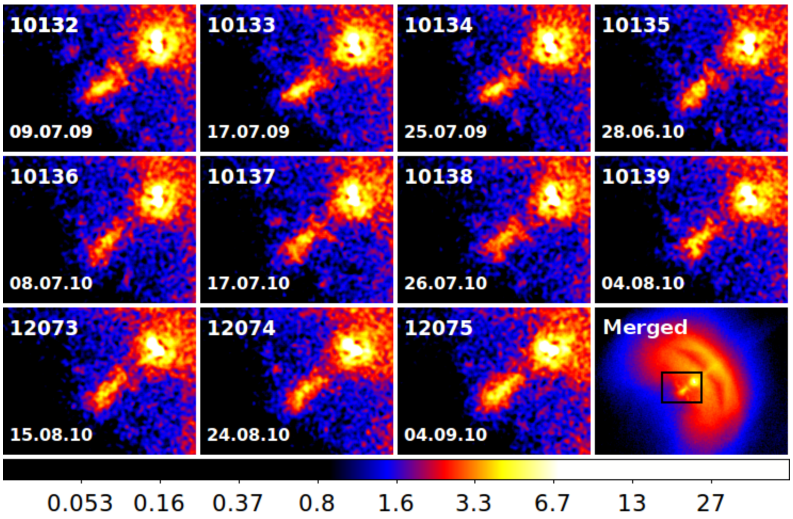

Figure 8. The X-ray maps of the vicinity ($22.8'' \times 16.5''$ area) of the Vela pulsar. The evolution of the southern jet *base* and the transverse *bar* is shown. First three images were made in 2009, the other eight – in 2010. In the lower right image the studied area is shown with a black box. The intensity scale is given for the images of individual observations, not for the merged one.

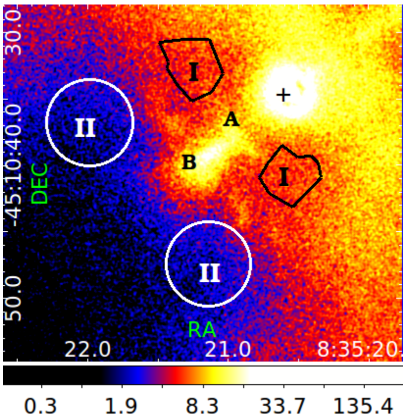

Figure 9. The summed X-ray image of the vicinity of the Vela pulsar: the *bar* (A) and the *base* of the southern jet (B) are shown. Black and white contours show the background areas used for spectral analysis of these structures.

background choices are: $\Gamma = 1.65 \pm 0.15$ for the *bar* and $\Gamma = 1.20 \pm 0.12$ for the *base* of the southern jet.

Notice that in Fig. 6 the photon indices of the individual observations of the southern jet's base appear softer (~ 1.25–1.35, though with larger uncertainties), since they were derived using yet another background (the region "7" in Fig. 2). In [10] the photon index of the southern jet base (termed there the "inner counter-jet") was estimated as $\Gamma = 1.20$ (with the *rms* deviation of 0.10) with the background consisting of two circles of 10.6 arcsec^2 each in the immediate vicinities northeast and southwest of the jet base. Another estimate $\Gamma = 1.36 \pm 0.04$ was recently given in [6], though the authors did not specify the background choice. Nevertheless, the spectrum of the *bar* is much softer than of the *jet base* and other PWN structures and its photon index resembles that of the emission of electrons accelerated at an ultrarelativistic collisionless shock.

3. Conclusions

Evolution of X-ray surface brightness and spectra of fine spatial structures in the Vela pulsar wind nebula (PWN) have been studied. The spectrum and dynamics of the transverse $4.5'' \times 1.5''$ *bar* within $4''$–$5''$ from the Vela pulsar, at the base of the southern jet of the nebula, was investigated. The *bar* can disappear and form again in ~ 10 days. Its power law photon index is much softer than that of the adjacent jet's *base* – 1.65 ± 0.15 vs 1.20 ± 0.12, respectively – and is close to 1.6, a typical value for synchrotron emission of electrons accelerated at an ultrarelativistic shock. Brightness, shape, and positions of the *bar* and the southern jet *base* vary on a timescale of 10 days. The *base* seems to "wiggle" – it curves and changes its inclination to the PWN's symmetry axis. We speculate that bright *blobs* seen on both sides of the southern jet *base* may have the same nature as the bright *blobs* on the terminaton shock ring of the Crab PWN, and thus might reveal the position of the termination shock of the Vela pulsar wind.

Acknowledgements

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Appendix

The choice of backgrounds in highly structured maps of extended X-ray emission is not obvious. It is especially non-trivial for the Vela PWN as it is rich in fine structures, which change their spatial extent and position, as well as brightness and spectral hardness, from observation to observation. Further complication comes from the probable presence of a weak bow shock embracing the whole nebula from the North [1, 4, 3]. The bow shock is formed where a mildly relativistic downstream of the TS of the pulsar wind encounters a weakly supersonic flow (of the Mach number ∼1.3), which hits the PWN from the North. The flow probably results from the passage of the asymmetric reverse shock of the supernova over the PWN. As such, the converging flows are shown to be highly effective in accelerating particles, which emit very hard X-ray spectra of $\Gamma \sim 1$ [2, 1]. Owing to their large mean free path, the X-ray emitting particles accelerated in the converging flows in Vela PWN may be partially responsible for the spectral hardness of its fine structures. For the same reason, the X-ray emission of the individual structures may overlap and appear as the diffuse emission embracing the whole nebula (which may account for ∼ 70% of the total emission of the PWN [9]). Since we are interested in the intrinsic spectra of the fine structures, two background regions "7" right outside the bright PWN were considered to subtract the contributions of the diffuse area and the bow shock emission, and to account for gradual weakening of the latter (as one moves away from the bow shock). However, if the spectra are fitted with the background shown by the dashed contours in Fig. 2), no significant difference is found in spectra and brightness (deviations were less than few %).

Table 1. Parameters used for the analysis of the X-ray maps of the Vela PWN in DS9. All Vela maps are made with the colormap "b". Gaussian function was used to smooth the images.

fig.	bin	contrast	bias	radius(px)	fig.	bin	contrast	bias	radius (px)
1	0.5	1.26	0.42	2	5	0.15	5.47	0.55	6
1 (inset)	0.1	2.4	0.43	5	8	0.25	3.43	0.56	3
2	0.5	1.26	0.42	2	9	0.15	2.7	0.43	3
4	0.25	2.6	0.45	3					

Table 2. Photon indices of the *bar* and *SE jet base* (3 sigma errors)

	bar		*SE jet base*	
background	Γ	C-stat/(1020 dof)	Γ	C-stat/(1020 dof)
I	$1.64^{+0.14}_{-0.13}$	1.03	1.14 ± 0.06	1.08
II	$1.60^{+0.08}_{-0.07}$	0.95	1.25 ± 0.04	1.01