On a previosly unknown X-ray feature of the Vela Nebula

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This paper tests the predictive power of a recently developed relativistic magnetohydrodynamic model of pulsar wind nebulae with a double-torus X-ray morphology. The model predicts highly-magnetized nebular flows should be quasi-laminar and split into two as they approach the outer boundary of the nebula. This prediction is shown to be supported by archival data from the Chandra X-ray telescope, which observed Vela, a double-torus X-ray nebula inflated by the pulsar PSR J0835−4510 in the constellation Vela. The model also explains the origin of part of Vela's diffuse X-ray emission.

Keywords: MHD, pulsar wind nebulae, supernova remnants, X-ray astrophysics.

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Introduction

The innermost area of the pulsar wind nebulae usually emits especially bright X-ray radiation. This area, called a compact nebula, begins right after the shock wave that terminates the pulsar wind. It is filled with shocked, highly-magnetized electron-positron $e^{\pm}$ plasma, supplied by the pulsar wind. X-ray radiation of the nebulae is induced by synchrotron radiation of high-energy nonthermal (accelerated) $e^{\pm}$ in the magnetic field of the background $e^{\pm}$ plasma of the nebulae. If a velocity of pulsar motion relative to an external medium does not much exceed a speed of sound in the medium, then the compact nebula usually acquires a jet-torus morphology, which can be of two types — with one torus or with two tori. The first magnetohydrodynamic (MHD) models of the single-torus nebulae were developed more than 20 years ago (see [1] and references therein), while the models of the double-torus ones were constructed quite recently [2–4]. The MHD models were prototyped by the single-torus Crab Nebula of the pulsar PSR B0531 +21 and by the double-torus Vela Nebula of the pulsar PSR J0835−4510 in the constellation of Vela.

1. Splitting of MHD-flows at the boundary of the compact nebula

Nebulae with a double X-ray torus are rare: currently, only 3–4 such objects have been discovered among the $\sim$100 nebulae observed in X-rays. The recently-constructed MHD model of the double-torus nebulae (Ponomarev et al., 2019, 2021, 2023) revealed a basic condition of their formation — stability of the pulsar wind termination shock. Here, stability refers to the regularity of the shock wave geometry. The shock's front should constantly maintain a smooth outline and not experience abrupt changes in size during the time it takes for the nebular flows to cross the nebula. Numerical simulation based on ideal magnetic hydrodynamics has shown that the front can be stabilized with a certain, quite rare combination of parameters of the pulsar, the pulsar wind and the external medium. The medium and the pulsar should move relative to each other at slightly supersonic, the pulsar wind should be low-magnetized and the pulsar should has a large angle of inclination of the magnetic axis to the rotation axis. It is precisely the need for weakly supersonic relative motion that makes this combination of parameters rare.. With this, the compact nebula forms a special structure of the MHD fluxes, a special structure of MHD flows develops in the compact nebula, due to which it acquires a double-torus X-ray morphology; for example, like one in the Vela's X-ray image in Fig. 1,*f*.

The structure of the MHD flows is clearly visible on the magnetic field maps on the poloidal section of the simulated double-torus nebula (Fig. 1). Fig. 1,*a* shows the simplified double-torus MHD model [2], while Fig. 1,*b* shows the realistic one [3,4]. In the simplified model, the nebula is at rest relative to the external matter, so the stability of its wind termination shock has to be maintained artificially. Artificiality means that a coarse numerical grid is applied at the initial stage of inflating the model. The coarse grid suppresses development of small-scale turbulence, preventing it from destabilizing the shock front. The simplified model is useful because it reveals a basic pattern of the flows in the double-torus objects. It is necessary to know this pattern for interpreting observation of real nebulae, in which the structure of flows can be slightly modified due to the motion of the nebula relative to the external medium. An example of such a modification is provided by the realistic model in Fig. 1,*b*. In this model, the compact nebula in a encounters a slightly supersonic flow of the external medium. This moderately-strong flow prevents the nebula from accumulating magnetic turbulence. This is facilitated by a special property of the double-torus nebulae: their

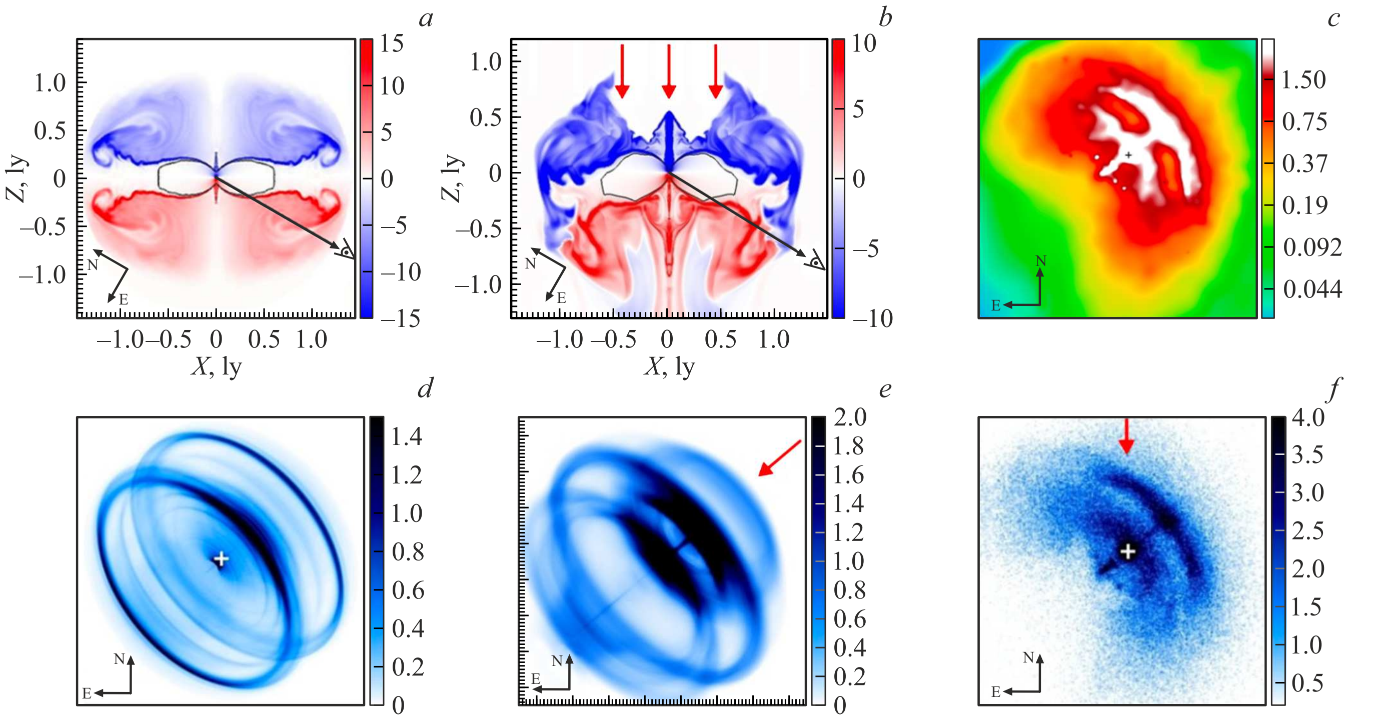

Figure 1. *a*, *b* — maps of the toroidal magnetic field (in units μG or 0.1 nT) of the simplified and realistic MHD models of the compact double-torus nebula (in its poloidal cut). The pulsar is in the center. The axes mark a distance in light years (ly). Two colors correspond to the different polarities of the MHD flows, and their intensities correspond to the magnetic field strength. Limits of the color scale are adjusted to emphasize a structure of MHD flows of the nebula. The black contour marks a position of the wind termination shock. Red arrows mark the direction of a weakly supersonic flow of the external medium, which onflows to the nebula along its polar axis (whose direction is determined by the pulsar rotation axis and vertical in the Figure). The black arrow coincides with line of sight of a terrestrial observer towards the Vela pulsar. The arrows *N* and *E* (north and east) mark an inclination of the Vela polar axis towards the Galactic north. *d*, *e* — synthetic maps of synchrotron X-ray emission of the simulated nebulae (*a* and *b*). These maps show the models in the same projection to the sky plane, in which the Vela is visible from Earth. The cross marks a position of the pulsar. The color means intensity of radiation of the simulated nebulae. The color scale (in arbitrary units) is inverse: the more saturated the color, the brighter emission. *f* — a Vela's X-ray image obtained by the Chandra telescope. *c* — a Vela's adaptively-smoothed X-ray image. The color scale (in the arbitrary units) is adjusted to emphasize splitting of wings of two bright Vela arches (the arches are marked in white).

driving-scale turbulence is excited at their outer boundary. There, the external flow can pick up large energy-containing turbulent vortices and draw them out of the compact nebula, thereby preventing them from cascading into its volume.

According to the magnetic maps in Fig. 1, the model nebulae include a wind termination shock, two highly-magnetized flows at the middle latitudes and a wide low-magnetized flow at the equator. The latter enters the nebula in an overpressured and underexpanded state relative to the adjacent highly-magnetized flows of opposite polarity running at the middle latitudes. The higher pressure at the equator prevents these flows (from different hemispheres) [5] meeting and mixing immediately behind the wind termination shock. As a result, these narrow flows remain quasi-laminar, relativistic and highly-magnetized throughout their entire length. As they approach the interface between the compact nebula and its external medium, the highly magnetized flows slow down, and each of them splits into two. Below the magnetic maps are shown maps of synchrotron X-ray radiation of the simplified and realistic models (Fig. 1, *d*, *e*). The simulated nebulae in them are represented in the same projection to the sky sphere, in which the Vela nebula is visible to the observer from the Earth. In this projection, the most distinct X-ray feature of the model is two coaxial tori that set atop each other. Halves of these tori, which are the nearest to the observer, are brightened due to the Doppler effect and visible as two parallel arches. These Doppler-brightened arches are produced by the two above-mentioned highly-magnetized flows (or rather, by those sections of them where the plasma moves at relativistic speed toward the observer).

This paper shows that reprocessing archival data from the Chandra X-ray Observatory allows us to reveal a new, previously unknown X-ray feature of Vela — a splitting of bright arches at the outer boundary of the compact nebula. This splitting is predicted by the realistic MHD model of the double-torus nebulae, but is not mentioned in the studies of the Vela observers [6–8]. Fig. 1, *c* shows the adaptively-smoothed image of the Vela, which demonstrates that the wings of the bright arches are indeed split. Adaptive

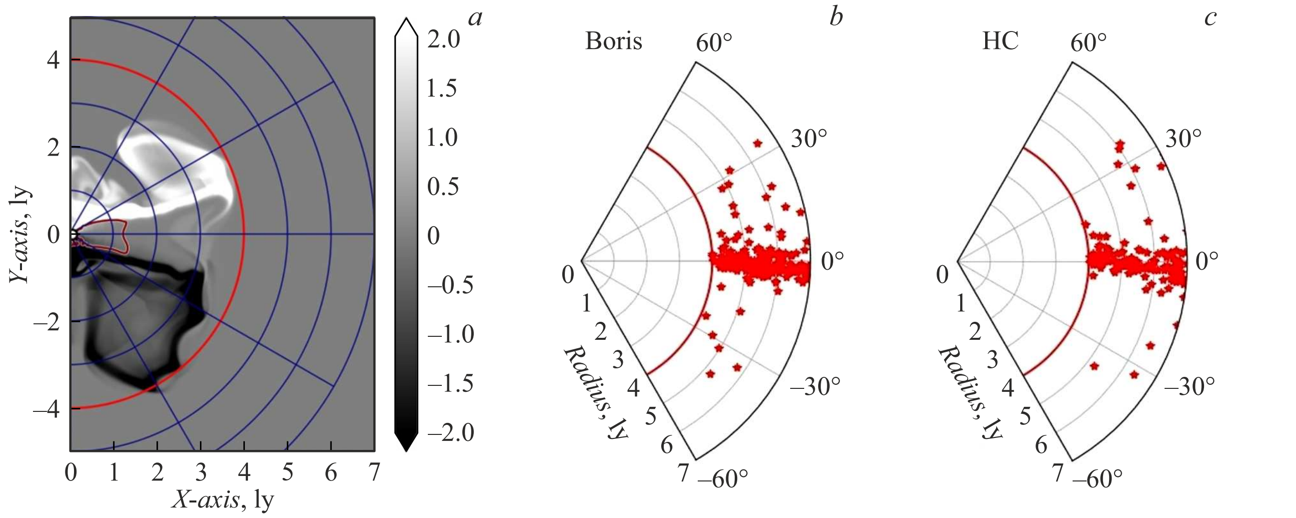

Figure 2. *a* — magnetic field map (in μG or in 0.1 nT) for the realistic model of the double-torus nebula (a half of the poloidal section of the axisymmetric model is shown). On the map, the pulsar's position is indicated by a white dot, the position of the pulsar wind termination shock by a dark-red outline, MHD flows of different magnetic polarity by black and white colors, an area of ejection of test e^- by a red line in the polar grid of coordinates. The range of the black-white scale is adjusted to highlight the structure of the flows, not the range of their fields. *b*, *c* — angular distributions of the tests e^- (red dots) with Lorentz-factors $\gamma \gtrsim 7 \cdot 10^8$ in 25 years after ejection, which are calculated by the methods of Boris and Higuera-Cary [12].

smoothing makes it possible to detect such splitting in all the 11 Chandra observations of the Vela in 2009–2010 (ObsID 10132–10139 and 12073–12075). Splitting can be observed not in all four wings simultaneously, which is not surprising, since the Vela flows are dynamic and can change their orientation relative to the observer [6,8].

2. Weak diffuse X-ray radiation of Vela

According to the Chandra, the double torus of the Vela is surrounded by weak diffuse X-ray radiation [8] Vela's radio maps exhibit two bright asymmetrical radio lobes, spread symmetrically relative to the symmetry axis of the double torus [9]. The radio lobes are probably brightened parts of a thick radiotorus that surrounds the double X-ray torus [9]. Non-thermal X-ray $e^\pm$, whose synchrotron radiation in the nebular magnetic fields (10–300 μG or 1–30 nT) falls within the Chandra X-ray range (0.5–8 keV), have energies reaching to tens and hundreds of teraelectronvolts (TeV), and the Lorentz factors (γ) 10^8–10^9. A place and a mechanism of acceleration of so energetic $e^\pm$ are still unknown [1]. One of the aims of the present study is to show that the realistic MHD model of the double-torus X-ray nebulae (Fig. 1) can provide acceleration of the $e^\pm$ to $\gamma \gtrsim 7 \cdot 10^8$. Let us that in the double-torus MHD models the nebular flows are quasi-laminar and the magnetic field is toroidal and regular. Based on the data of the X-ray polarimeter IXPE, Xi et al. (2022) confirmed presence of these properties in the Vela. In the quasi-laminar flows, $e^\pm$ can accelerated in shear flows. This is exactly what we observed in our model double-torus nebula when we injected test non-thermal particles (e^-) into it and traced their evolution in space and energies.

Dynamics of the MHD flows of the background plasma of the nebula was simulated by means of an „RMHD“ module of an PLUTO open numerical code based on the system of equations of the ideal relativistic MHD [10] Dynamics of the nonthermal test e^- in the MHD flows was traced using the Boris algorithm embedded into the „Cosmic Rays“ module of the same code [11]. Simultaneous modeling of MHD flow dynamics and test e^- dynamics is very resource-intensive, so at the initial stage of the research we used a simplified approach. Before ejecting test particles into the simulated nebula, we evolved it to the stage of self-similar expansion, and then „froze“ the entire pattern of its MHD flows. In terms of the test particles, this pattern looked like a stationary one (i.e., the magnetic field, the pressure and the background plasma velocity in each point of the simulated nebula did not change during the entire process of particle acceleration). This simplification would be unreasonable with respect to the single-torus nebulae with their turbulent MHD flows, in which e^- are most likely accelerated by scattering on random magnetic inhomogeneities. However, with respect to the double-torus nebulae with their quasi-laminar shear MHD flows and the regular fields this approximation is quite allowable. During simulation, a population of 3.5 million electron particles with $\gamma = 10^7$ was ejected once homogeneously and isotropically into the fully inflated nebula with the „frozen“ structure of MHD flows. Fig. 2 shows a simulation result — the angular distribution of the test e^-, that were able to accelerate in the MHD fluxes of the nebula to $\gamma \gtrsim 7 \cdot 10^8$ (to $E \gtrsim 350$ TeV). In the assumed magnetic fields of the radiotorus (0.5–5 μG or $0.05-0.5$ nT), synchrotron radiation of such e^- falls into the Chandra sensitivity range. Their angular distribution is highly anisotropic — they escape the compact nebula primarily along a plane of its equator (Fig. 2). A similar distribution is formed by test radio electrons ejected into the simulated nebula. This indicates that the similarity in the spatial distributions of the diffuse X-ray and radio emissions from Vela may be due to the similarity in the angular distributions of non-thermal radio- and X-ray (with $E \gtrsim 350$ TeV) particles escaping the compact nebula.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix 1. Parameters of the MHD models of the double-torus pulsar nebula

The following parameters are chosen for MHD models of nebulae: the inclination of the pulsar — α, initial magnetization of the pulsar wind — σ_0, Mach number of the directed external flow — M, and the density this flow — ρ_{amb}. In the realistic model in Fig. 1: $\alpha = 80^0$; $\sigma_0 = 0.1$; $\rho_{amb} = 10^{-28}$ g/cm^3; $M = 2.3$. In the model in Fig. 2 $\alpha = 80^0$; $\sigma_0 = 0.1$; $\rho_{amb} = 10^{-29}$ g/cm^3; $M = 1.3$. The pulsar wind model accepted in the calculations is described in the study [4]; the wind power is normalized to the power of rotational energy losses of the Vela pulsar ($6.9 \cdot 10^{36}$ erg/s).

Appendix 2. Description of parameters of adaptive smoothing

The adaptively smoothed images were obtained by means of the „csmooth“ algorithm embedded into the „CIAO“ software of the Chandra X-ray telescope. The „csmooth“ parameters: the method — FFT (Fast Fourier Transformation); the kernel type — Gaussian; $(S/N)_{\min} = 3$, $(S/N)_{\max} = 5$; the minimum core size — a pixel size of the ACIS detector, the maximum core size — is a size of the entire image; the initial step of increase of the core size is 0.01 of the ACIS pixel.