Two tori of the Vela pulsar wind nebula

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Abstract. In the frame of the axisymmetric relativistic magnetohydrodynamic simulations we show that the double-arc feature of the Vela pulsar wind nebula (PWN) visible in soft X-rays can be reproduced at high inclination (obliquity) of the Vela pulsar and low magnetization of its wind provided the turbulent and magnetic energies of the nebula dissipate effectively. In that case, the arcs represent the Doppler brightened regions of two persistent large-scale toroidal whirls of strongly magnetized plasma located below and above the wide low-magnetized equatorial belt of the nebula. If the long-term persistence of the large-scale magnetic structures would be confirmed in more realistic simulations, the difference in X-ray morphology of the Crab and Vela PWNe can be explained by the difference in spin-down and inclination of their parent pulsars, and not by the very different magnetization of their winds, as supposed earlier.

1. Introduction

Rotation powered magnetized neutron star (a pulsar) converts most of its rotational energy into a cold relativistic particle outflow – a pulsar wind. The theory of pulsar magnetospheres predicts that the wind is strongly magnetized (Poynting dominated) at its base and carries along a toroidal magnetic field frozen into the electron-positron plasma [21]. Since the wind is supersonic, it drives a shock into an ambient medium. Downstream this termination shock (TS) the wind inflates a synchrotron emitting plasma bubble known as a “pulsar wind nebula”, PWN. To date, the synchrotron nebulae are found around ∼ 100 young and middle-aged pulsars [13].

Observed PWNe exhibit a plenty of morphologies [12]. Among them there are ones resembling a torus (or tori) and jets – strongly collimated outflows emanating along torus symmetry axis. The best studied objects of this type are the Crab and the Vela nebulae. Together with their parent pulsars Crab and Vela, they were intensively observed over the past decades and resolved in space down to a few light days, and in time – down to a week scale [5, 13].

It is believed that morphology and time-integrated energy budget of a PWN bear the imprint of the properties of its parent pulsar. In particular, the nebula keeps memory about the angle α between the magnetic and the rotational axes of the pulsar (i.e., the pulsar inclination), the spin-down luminosity $L_{sd}$ of the pulsar, and the wind magnetization $\sigma$ – the ratio of magnetic to particle energy densities measured in the fluid frame. Of course, the PWN-pulsar correlation holds if the nebula is not distorted by the ram pressure of the ambient medium, e.g. [3, 2, 17].

Over the past years, many groups presented quantitative PWNe models built within the framework of the ideal relativistic magnetohydrodynamics (RMHD). Both the axisymmetric (2D) [15, 8, 1, 6, 22, 7, 6] and the three-dimensional (3D) [20, 2, 17] models were developed. They provided a deep insight into the dynamics of magnetized plasma flows within PWNe. However, no definite answer is given as yet why in soft X-rays the Crab PWN is visible as a
single torus, while the Vela PWN exhibits two bright arcs [11, 18, 10]. These arcs centered onto
the PWN symmetry axis are separated by the region of distinctly suppressed X-ray brightness.

With its two arcs, the Vela PWN looks axially elongated, compared to the Crab PWN. It
was supposed earlier [11] that Vela’s elongation might be explained by the enhanced hoop stress
in the nebula due to a higher initial magnetization of Vela’s wind: σ0 ~ 1 vs σ0 ~ 0.01 in Crab.

Subsequent 2D simulations [15, 9, 22, 7, 20, 6] found some hints that synthetic X-ray synchrotron
maps of PWNe may exhibit multiple arcs of similar size if the pulsar wind has a 2–3 orders of
magnitude higher σ0 than Crab’s one, as exemplified in Appendix A1. However, in no case these
arcs were attributed to persistent structures in the PWN. The studies rather aimed to explain
the appearance of bright arc-like features in the X-ray images.

To reassert these conclusions and to check if any other plausible explanations of the Vela
double-arc structure are possible, we run the 2D RMHD simulations of the PWN (with northern
and southern hemispheres calculated independently). We use the same setup as Bühler & Giomi
(2016) [6] and the RMHD module of the PLUTO code [16] with an adaptive mesh refinement
(AMR) applied whenever required to resolve small-scale structures in the nebula. The code
normalization units and the grid parameters are given in Appendices A2, A3.

2. Results
The pulsar wind does not radiate (its thermal energy is negligible compared with the kinetic and
magnetic energies), and its properties are not known with certainty. Nonetheless, observational
and theoretical studies indicate that the power of the wind, probably, scales as sin^2 θ, where
the angle θ (colatitude) is measured from the rotational axis. This causes the TS to acquire an
oblate shape (with the funnels at the poles) and leads to an aspherical PWN. Due to the pulsar
inclination, the wind sector of angular extent ±α around the equator carries along the stripes of
the alternating magnetic polarity which may, presumably, annihilate. For this reason, the wind
initial magnetization σ0 may differ from the magnetization ⟨σ⟩ averaged over the wind volume.

In our simulations we reproduce the most generic patterns of the plasma flow within nebulae
found in earlier studies (e.g., [9, 22, 20, 6]). We also observe the high degree of post-shock
turbulence, and the hoop-like backward flow patterns emerging within the shear flow in the TS
immediate downstream reported in [9, 7, 6].

Meantime, the simulations show that an axially elongated model of a PWN like Vela’s one
may be built without invoking the high σ0. The "aspect ratio" of a TS and an adjacent inner
nebula are driven rather by an average magnetization ⟨σ⟩ which accounts for the field dissipation
in the striped wind and depends on both α and σ0 (however, a PWN may have different rates of
dissipation of magnetic and turbulent energies in its different regions. This may affect the PWN
“aspect ratio” as well). This conclusion is in agreement with the recent 2D study [6] and stays
robust even in 3D. 3D shocks have axial and equatorial sizes either similar to the corresponding
2D ones (at low σ0 ~ 0.01), or larger in ~ 2 and 1.5 times, respectively (at high σ0 ≥ 1) [20].

The observations do not favour the higher magnetization of Vela’s wind as well. The standard
estimations suggest that the Crab and Vela pulsars possess the similar magnetic fields at their
surface — lg Bs = 12.58 and 12.53 — which reduce to lg BLC = 5.96 and 4.65 upon approaching
their light cylinders (LC) [14]. We, therefore, do not constrain our simulations of the Vela PWN
morphology to the high σ0 cases only. The runs are made at various combinations of (α, σ0)-
values within the ranges 10°–80° and 0.03–3.0. The aim of the study is to find at which (α, σ0)
the synthetic X-ray synchrotron map provides the best fit to the observed X-ray map of the Vela
PWN with its two bright arcs and the under-luminous region in-between permanently visible
for ~11 years.

We prefer, however, to think about two tori in the PWN, and not the double-arc feature,
for the following reasons. First, Vela’s X-ray images [15] indicate that at least the lower arc of
the nebula is a brightened part of some toroid. The latter shows up its distant parts via the
backbend of arc’s wings and via the barely visible “necklace” of bright blobs [19] (resembling the bright X-ray blobs in the Crab TS). Second, one can reasonably expect that all PWNe of jet-torus morphology make their tori in the same way as Crab does: the highly-magnetized post-shock outflow loses its radial velocity under the action of the hoop stress of the magnetic field and produces a sort of a large scale vortex-shaft (forming a torus in 3D).

We begin our the study, however, not from the tori but from the ‘dark’ region in-between. Its persistently lower synchrotron emission suggests a persistently lower magnetization therein, as the particles of energy $\sim 10–100$ TeV producing the X-ray emission have the mean free path comparable to the PWN extent. Generally, a weakly magnetized region naturally emerges in the vicinity of the Mach belt — the distant near-equatorial end of the TS perpendicular to the striped wind stream. For that region to have a wide axial extent, the striped stream must fill almost the entire wind volume, that is, the pulsar magnetic axis must make a large angle $\alpha$ to its rotational axis. To stay weakly magnetized persistently, the region has to be unperturbed by the violent magnetic vorticity generated by the sheared downstreams running along the oblique parts of the TS (in the northern and southern PWN hemispheres, respectively).

Therefore, in order to explain the extended under-luminous region between Vela’s tori, one can just make two assumptions: (1) that the Vela pulsar has a high inclination ($\alpha \sim 60^\circ–80^\circ$) and (2) that Vela’s wind is low magnetized ($\sigma_0 \sim 0.01–0.03$). The assumption about high $\alpha$ would be in agreement with some interpretations of the gamma-ray light curve of the Vela pulsar ($\alpha \in 62^\circ–75^\circ$) [1] and some models of the pulsar magnetosphere ($\alpha \in 40^\circ–90^\circ$) [14].

More importantly, at high $\alpha$ the post-shock hoop stress and turbulent vorticity develop at very high latitudes [9] and perturb only the high-latitudinal parts of the TS. Throughout the rest of its extent the TS remains steady if the vorticity is not too powerful. In this respect, the second assumption about the low magnetization $\sigma_0$ is also important: it allows to quench this detrimental vorticity (in 2D — see section 3 in 3D — see in [20]), while leaving the size of the high-$\alpha$ shock almost unchanged [10]. All in all, at high $\alpha$ and low $\sigma_0$, the sheared downstream does not carry along the strong perturbations and does not launch them into the nebula. Instead, its bulk flow enters the nebula smoothly at mid-latitudes and stays collimated up to the edge of the nebula, thereby leaving the equatorial belt unperturbed and spectacularly low magnetized. Since the slow equatorial outflow is over-pressured and under-expanded (as follows from the simulated pressure maps), its post-shock expansion gradually deviates the mid-latitudinal magnetized outstreams further away from the equator, into the northern and southern PWN hemispheres. There the outstreams lose their radial velocity under the action of the hoop stress of the magnetic field and merge into the large-scale whirls — one in the northern hemisphere and one in the southern one. In this way two toroidal structures form in the PWN.

The velocity and magnetic field maps of 2D PWN model are shown in the upper panels in figure 1. The case with $\alpha = 80^\circ$ and $\sigma_0 = 0.03$ is presented, for comparison with the earlier work [6]. The synthetic synchrotron X-ray map of this nebula exhibits remarkable double-arc feature with the pronounced ‘dark’ region between the arcs, as evident from the upper right plot. The one important caveat has to be put, however: such a nebula is built in the run where a coarse spatial grid is used until the nebula ages up to $\sim 6–8$ years (when it enters the self-similar expansion phase), and only then the AMR is enabled to allow the small-scale vortices to develop in the TS immediate downstream. The reason for this trick is explained in section 3.

To facilitate the following explanations, we give in figure 1 two additional PWN models. The middle panels show the same ($80^\circ$, 0.03)-case as the upper panels but the PWN is built in the run where the fine spatial grid is used from the beginning to the end of the calculations. Finally, the lower panels show the ($45^\circ$, 3)-case where again, as in the upper panels, the coarse grid is utilized until $t = 8$ years and the AMR later on. Needless to say, that these two PWN models neither exhibit the clear double-arc feature, nor show the extended ‘dark’ regions between their multiple bright arcs somewhere in their synthetic synchrotron maps.
Figure 1: $2.8 \times 2.8$ l.yr 2D–maps of the simulated PWN at the age $t = 10$ yr. The left panels (A,D,G) show the plasma velocity magnitude in units of $c$; the middle panels (B,E,H) – the plasma azimuthal magnetic field in $\mu G$; the right panels (C,F,I) – the synthetic synchrotron maps (the brightness is linearly scaled in arbitrary units) of the nebula viewed at the angle of $127^\circ$ (shown by thin line) and rotated in the sky plane to the position angle of the Vela PWN ($130^\circ$). The upper maps (A,B,C) stand for the case when the pulsar has the inclination $\alpha = 80^\circ$ and the initial wind magnetization $\sigma_0 = 0.03$, and the run is made with the coarse grid until $t = 8$ yr and with the AMR later on. The maps (D,E,F) in the middle row display the same case ($80^\circ$, 0.03) but with the fine grid used all along the run (the static cylindrical grid with the cell size of $2 \times 10^{-3}$ l.yr.). The bottom maps (G,H,I) show the case of $\alpha = 45^\circ$ and $\sigma = 3$ where, as in the upper maps, the coarse grid is used until $t = 8$ yr and the AMR afterwards.

3. Discussion
The results of the 2D RMHD simulations shown above infer that double-arc feature of the Vela PWN visible in soft X-rays might be associated with the Doppler brightened parts of two toroidal structures. They represent two detached persistent large-scale whirls of strongly magnetized plasma below and above the low-magnetized equatorial belt of the nebula. Such whirls may form if the pulsar has a large inclination ($\alpha \sim 60^\circ$–$80^\circ$) and a low magnetized wind ($\sigma_0 \sim 0.01$), provided the magnetic and turbulent energies dissipate effectively in the PWN outskirts.
Since the RMHD module of PLUTO code does not account for dissipation (although its fine spatial grid allows cascading of magnetic and turbulent structures from large to small scales, where they could dissipate), we can not check directly whether the trivial assumption accepted above is workable in explaining the Vela arcs with the ‘dark’ region in-between. To circumvent this problem in the numerical scheme, we suppress the small-scale vorticity artificially, until the nebula appears to be fully inflated. We run the calculations on a coarse grid which smooths out the small-scale perturbations and quenches the short-term shock variability. This trick allows us to get some idea of what the mature nebula would look like if its post-Mach belt outflow could stay persistently low magnetized and if the excessive magnetic vorticity in its outskirts would not have developed.

To this end, several runs are made where a coarse spatial grid is used until the PWN reaches the age of 6–8 years when the shock turns out to be fully inflated but the nebula outskirts have not yet built up an excessive vorticity and magnetization. After that, the adaptive mesh refinement is enabled, which allows the shock to develop vorticity in its vicinity. The outcome of such a run, for the case $\alpha=80^\circ$, $\sigma=0.03$ is given in the upper panels in figure 1. One can see that the magnetized outflow do not converge toward the equator and the synchrotron X-ray map does exhibit the clear double-arc feature with the wide under-luminous region in-between.

The bottom panels show the case $\alpha=45^\circ$, $\sigma=3.0$ well-studied in the literature. They illustrate that the mentioned features do not appear on the X-ray map, if the pulsar does not have a large inclination and a low magnetized wind. Here we show the maps built in the run with the coarse grid up to 8 yrs and the AMR later on. The maps for same case but built in the fine grid run one can find, e.g., in [9, 6]. Whatever grid is used for, the X-ray maps for the ($45^\circ$, 3.0)-case reveal a compact and axially elongated PWN, with a plenty of arcs and other bright structures of similar size [9, 6]. But neither the clear double-arc feature, nor a ‘dark’ region between some arcs in the PWN are seen.

Finally, the middle-row maps in figure 1 the PWN model show the artifacts of the axisymmetrical ideal RMHD simulations. These artifacts force us to use the trick with the coarse grid, since they hinder and preclude the formation of the well-shaped persistent structures in the nebula whose presence is revealed by the X-ray observations of the Crab and Vela PWNe. The model shows the (80$^\circ$, 0.03)-case as the one in the upper-row maps but built in the run with the fine grid used from the beginning. In contrast to the upper-row model, the PWN exhibits an over-developed vorticity and magnetization. Both artifacts develop since the 2D-shock is very unstable in the absence of the dissipation of magnetic and turbulent energies.

In the fine resolution 2D runs, the TS never remains steady and distorts all the time, from its funnels to the Mach belt, changing its size and shape less than in a month time scale. This induces the strong turbulence in the shock vicinities and accumulates there, in the absence of dissipation, an excessive energy of the magnetic field. The field, in turn, excites and sustains the shock variability [7, 20]. In such a model, the post-shock high-velocity flow patches of enhanced magnetization instantly streaming toward the observer all the time emerge at different locations and in different numbers. As the result, the Doppler-brightened features (arcs in 2D) in the synthetic X-ray maps are highly variable in number, location and brightness, and are very short-living. The synchrotron map of this model does exhibit multiple arc-like features, as in the middle right panel in figure 1 but none of these bright (or ‘dark’) features persist more than a (few) month(s). Meanwhile, the toroidal whirls in the upper-row model steadily develop in a few month after the AMR is enabled and then persist for at least 4-5 years (until the PWN builds up an excessive magnetization again).

The over-developed magnetization/vorticity acquired by the 2D PWN in 5-10 years after its birth are detrimental not for the shock size and stability only. As soon as the first large-scale vortex launched into the PWN outskirts comes back to the shock and hits it, the shock loses any connection of its characteristics with the properties of the parent pulsar, and never recovers.
it afterwards. Instead, it begins to reverberate until the approach of the new large vortex from the outskirts, and the process repeats again. All that produces so strong and stochastic large-scale vorticity in the nebula that it may not only crash the shock but wear out any signs of the symmetry in the whole nebula within dozen years.

Finally, one more interesting feature on the upper-row synchrotron map is apparent: the distant part of the lower torus appears to be Doppler-brightened too. This happens due to the Y-like splitting of one magnetized whirl in two counter-rotating whirls (the phenomenon is routinely observed in MHD). The absence of this feature in the observed X-ray map suggests that in the real PWN this large-scale whirl should retain its integrity. More realistic 3D simulations which account for dissipative effects are needed to explain the long persistence of the large-scale magnetic structures observed in PWNe.

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Appendix

A1. The best fits from the recent work [6]: for Vela ($\alpha, \sigma_0 = (45^\circ, 3.0)$, for Crab ($\alpha, \sigma_0 = \{80^\circ, 0.03\}; 80^\circ, 3.0\}; (45^\circ, 0.03); (10^\circ, 0.03)\}$. These fits imply the average magnetizations $\langle \sigma \rangle = 0.12$ in the Vela PWN and $\langle \sigma \rangle = \{0.0014; 0.0038; 0.0043; 0.024\}$ in the Crab PWN.

A2. Normalization units of the code primitive variables: density – $10^{012013}$, pressure – $10^{349} G$, speed – speed of light, magnetic field – $3.66 \cdot 10^{-3} G$, pressure – $8.99 \cdot 10^{-7} dyn \ cm^{-2}$. The length scale is 1 light year (l. yr.). $\sigma(\theta, \alpha) –$ the dependence of wind’s magnetization on colatitude and inclination, the wind Lorentz factor $\Gamma = 10$, and the synchrotron mapping recipe are the same as in [6].

A3. The simulated region is $r < 0.0002 \div 1.4$ l.yr. The coarse spherical grid has 88 logarithmic radial bins (with the spatial resolution $\Delta r \sim 0.03$ l.yr. near the TS) and 32 polar angle bins in $\theta \in [0 \div \pi$]. The AMR is applied with 4 levels and the refinement ratio = 2 (the equivalent grid is $1048 \times 512$ cells at the 4th level, with $\Delta r \sim 0.0003-0.0003$ l.yr near the TS).

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