Jet and counter-jet in transonic pulsar wind nebulae

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Abstract. X-ray observations show that a jet and a counter-jet in pulsar wind nebulae often differ one from another. Sometimes one of the jets is not observed at all. We show that the most likely reason for this difference is the relative motion of a pulsar and an ambient matter. Even the slow (subsonic or transonic) ambient matter stream in the pulsar rest frame strongly affects the jets, making the windward jet bright and dynamic, and the leeward jet dim and diffuse. The effect is illustrated using a relativistic MHD model of a double-torus pulsar wind nebula. The model is shown to explain reasonably well the observational appearance of the jets in the Vela nebula – a double-torus object which evolves in a transonic stream initiated by the passage of the reverse shock of the parent supernova.

1. Introduction
Pulsar wind nebulae (PWNe) are bubbles of relativistic magnetized electron-positron ($e^\pm$) plasma, blown by the rapidly rotating magnetized neutron stars – pulsars. The ultrarelativistic pulsar wind carries along an azimuthal magnetic field frozen into the plasma and, being supersonic, drives a shock into the ambient medium. Downstream this termination shock (TS) a synchrotron emitting nebula is inflated. To date, about 100 PWNe are known [10]. PWNe may have different morphologies [9]. Here we focus on a sub-class of jet-torus PWNe. They are believed to move relatively slow with regard to the ambient matter, so that their jet-torus structure is not destroyed by this motion. In this study, we are interested in the X-ray morphology of jets – collimated polar outflows emanating along the nebula’s axis of symmetry (which coincides with the projection of the pulsar’s spin axis and the torus/tori symmetry axis).

None of the observed jet-torus PWNe have a jet and a counter-jet similar to one another (for the images, see, e.g., [9]). Jets are formed downstream of the TS of the pulsar wind [12, 2], but the wind on its own cannot be the cause of the different appearance of the opposite jets. The angular distribution of the wind’s power is believed to scale as $\sin^2 \theta$ (where $\theta$ is the colatitude with respect to the PWN’s axis of symmetry) [1], so the wind is symmetric relative to the plane of the PWN equator. In this case, jets should form at nearly the same conditions and the same distance from the pulsar. Like any plasma pinches, the jets have inertia [16] and are prone to instabilities. Therefore, they are sensitive to the neighbouring plasma flows. If the flows in the nebula’s hemispheres develop more or less independently, then at any given moment, the opposite jets do not have to be identical. However, over long periods of observations, one would expect that their overall appearance should be more or less the same. Meanwhile, the opposite jets in the Crab and Vela PWNe, observed in detail for about two decades, are very different from each other. The reason for this difference is still unknown; most often it is attributed to the
difference in orientations of their jet and counter-jet relative to our line of sight, which results in different Doppler corrections to the brightness of their emission. However, in the Dragonfly and 3C58 PWNe viewed edge-on (their axes make $\approx 86^\circ$ \cite{23} and $\approx 92^\circ$ \cite{17} to the line of sight), the opposite jets are visible at the same angle, and yet very different (see Fig. 1 in \cite{23} and the map 5 in Fig. 2 in \cite{9}). Sometimes, the dissimilarity of the jets is explained by a density gradient in surrounding matter, but arguments in favour of the presence of such, and an explanation of the reasons for its occurrence, are usually not given. In our work, using the relativistic MHD model of a double-torus PWN \cite{21} as an example, we show that taking into account the motion of the ambient matter in the rest frame of the pulsar makes it possible to explain the dissimilarity and substructures of the jets in the Vela PWN.

2. Problem setup

In our setup, a pulsar at rest meets a steady-state stream of surrounding matter. The stream is initiated at once in the entire computation domain. Then, within this stream, a double-torus PWN is inflated. Its axis is co-aligned with the stream, for simplicity. Hereinafter, we will call the stream-facing hemisphere of a PWN the windward one, and the opposite hemisphere the leeward (lee) hemisphere. The jet that meet the stream head-on will be called the jet, and the opposite jet – the counter-jet.

We run our simulations with the RMHD module of the PLUTO code \cite{15} (see Appendix for details). The setup of the problem is chosen as to maximize the effect of the motion. First, the upper limit of a slow relative motion is considered – transonic motion, which translates to the Mach number $M_s = 1$. Second, a double-torus PWN model, suggested in \cite{21}, is employed. In this model, highly magnetized plasma outflows of opposite magnetic polarities, feeding the jet and torus in each hemisphere of the nebula, develop almost independently from each other (being separated by a wide weakly-magnetized equatorial outflow, which mediates their interaction). As shown in \cite{21, 14}, the double-torus nebula may form around a pulsar with high magnetic inclination ($\alpha \gtrsim 70^\circ$) and low-magnetized wind ($\sigma_0 \lesssim 0.1$; $\langle \sigma \rangle \lesssim 0.003$). Here $\alpha$ is the angle between the magnetic and spin axes of the pulsar and $\sigma_0$ and $\langle \sigma \rangle$ are the initial and the average magnetization of the pulsar wind (the ratio of the magnetic to kinetic energy fluxes). In this study, we put $\alpha = 80^\circ$ and $\sigma_0 = 0.1$, which results in $\langle \sigma \rangle = 0.00066$ due to the dissipation of the magnetic field in the striped sector of the wind \cite{11, 22}. Third, as mentioned above, the stream and the PWN axis are taken to be co-directional, since in this case the jet and the counter-jet will be maximally different.

Such setup has the advantage of checking our PWN model against observations. The Chandra telescope provided a high-resolution X-ray images of the nearby double-torus PWN Vela \cite{18, 8}. Due to the proximity of this nebula to Earth ($d \approx 290$ pc), its X-ray morphology is resolved down to $\approx 1$ light day, so the morphological difference between its jets can be traced down to the finest detail. X-ray and radio observations indicate that this nebula develops in an oncoming stream with a Mach number of $M_s \approx 1.3$, initiated by the passage of the reverse shock of the supernova \cite{5}. At variance with our model, the stream makes an angle of $\approx 60^\circ$ to the Vela’s symmetry axis. Even so, our simplified model is capable of reproducing the key properties of both Vela’s jets.

3. Results

In a static or radially expanding ambient matter (in the pulsar’s rest frame), a double-torus PWN is almost symmetric about its equatorial plane (hence the plane of the pulsar’s rotational

\footnote{The striped wind is formed within the sector $\pm \alpha$ around the rotational equator of the pulsar; it is filled with the stripes of alternating magnetic polarities, which are believed to annihilate before the wind enters the nebula \cite{4}}
equator) \cite{21}, although such symmetry is not assumed by the 2.5D geometry of our problem. The stream, even a slow one, modifies flow patterns in the PWN, so the latter can no longer maintain the symmetry between its hemispheres. In our setup, where a PWN is weakly magnetized, and from the very beginning develops in an oncoming stream (instead of colliding with it at the stage of self-similar expansion, being already developed), the stream can penetrate deep into the windward PWN hemisphere. The difference in the morphology of the jets develops due to their interaction with the stream and with the surrounding plasma flows, also affected by this stream. To illustrate the problem, in figure 1 we show 2D maps of the PWN, with plasma parameters (velocity, density, pressure, magnetic field) that determine synchrotron radiation of the nebula. The synthetic map of this radiation is then to be compared with the actual X-ray map of the Vela PWN, to see how well our model captures the flow patterns in the real nebula.

In the transonic double-torus PWN, the tori – large-scale toroidal vortices – are represented by the circulation flows (one per hemisphere) that develop at the mid latitudes of the nebula on either side of its equatorial plane. When the stream advances into the windward hemisphere, the windward circulation is pushed away from the axis, so that it can no longer affect the jet and the latter may interact directly with the stream, meeting it head-on. In the opposite hemisphere, the situation is different. As the stream wraps around the PWN, the lee circulation is pushed inward, so that it nearly converges at the axis. Since the tori reverberate (see \cite{13} in these proceedings), the circulation flow sometimes converges so closely that almost chokes the counter-jet. So that the latter often cannot break through the circulation flow and completely fits into the volume occupied by the lee torus. The backflow from the head of the counter-jet evolves differently than the backflow of the opposite jet. While the latter is pressed by the stream against the jet’s spine, forming a sort of a tight sheath stretching down to the jet origin, the backflow of the counter-jet is pulled away from the spine due to entrainment by the neighbouring circulation. When the circulation brings the backflow to the point where the TS funnel passes into the arched vault, the backflow split in two – one part of it is drawn into circulation, the other dives into the funnel and forms a stable toroidal eddy there (hereinafter, the in-funnel eddy). This eddy can be seen on the maps in figure 1 near the base of the counter-jet. The in-funnel eddy is very dynamic (but persistent) and has a sense of rotation opposite to the circulation flow. Since the counter-jet is formed inside the same funnel, its interaction with the neighbouring eddy affects its morphology no less than the interaction with the circulation flow.

3.1. Jet
In our setup, the stream penetrates into the windward hemisphere along the nebula’s symmetry axis. So that the windward jet, at some point, leaves the nebula and advances into the stream. In this regard, this jet is subdivided into two characteristic segments. The inner part, within the nebula and the outer extension pushing against the stream. Interestingly, that in the Vela PWN, the windward (NW) jet does have two characteristic segments (dubbed as ”inner jet” and ”outer jet” in \cite{19}). The ”outer jet” is very dynamic because, unlike our setup, it meets an oblique stream, which makes an angle of $\sim 60^\circ$ to the PWN axis.

3.2. Counter-jet
Two vortices, closely interacting with the counter-jet – the circulation flow and the in-funnel eddy – naturally subdivide this jet into three characteristic segments: two ”inner” segments, protected from the stream by the lee torus, and the outer one.

The first inner segment – the base of the counter-jet – extends from its origin to the entrance to the eddy. It is quite feeble compared to the base of the opposite jet – much thinner, less magnetized (because the lee TS funnel in a moving nebula is located farther from the pulsar, see \cite{13} in these proceedings)) and less dense. Hence, the base is almost indiscernible on the synchrotron map.
velocity, $v/c$
density, $g/cm^3$
pressure, $dyn/cm^2$
azimuthal $B$, $\mu G$
synthetic X-ray map
Vela PWN: X-ray map

Figure 1: Left to right, top to bottom: velocity, density, pressure and magnetic field maps in the model nebula, followed by a map of its synthetic synchrotron X-ray radiation and the summed (440 ks) Chandra X-ray (0.5-8 keV) image of the Vela PWN (PI: G.G. Pavlov). The model assumes that a pulsar (marked by black cross) with a high inclination ($\alpha = 80^\circ$) and low magnetized wind ($\sigma_0 = 0.1$) inflates its PWN, being in a stream (shown by red arrow) with Mach number of 1.3 co-directional with the PWN axis. On the synthetic map, the brightness is square root scaled, in arbitrary units, and the PWN is shown as the Vela PWN is seen from Earth: the PWN axis is tilted to the sky plane so that its NW (windward) end makes $\theta_{\text{view}} = 120^\circ$ to the line of sight (shown by black arrow), and rotated in the sky plane to the P.A. of 130$^\circ$ measured north through east [8, 17]. On the Vela image, a yellow arrow depicts the likely direction of the transonic stream the Vela pulsar meets in its rest frame [5].

The second – middle – segment, extending from the eddy to the exit of the circulation flow, in contrast, is quite bright. Here, the polar outflow slows down due to compression (as it is nearly choked downstream) and becomes much denser, more magnetized and pressurized. In this regard, the counter-jet becomes visible on the synchrotron map only at some distance from the pulsar. Interestingly, that the bright segment of the SE (counter-)jet in the Vela PWN behaves in a similar fashion: it emerges $\sim 5''/4$ from the Vela pulsar and extends outward up to $\sim 10''/5$, and then fades away [10]. Moreover, this bright segments seems to actually fit into the
SE torus, which is $\approx 10''$ in diameter (this minor diameter of the torus is estimated as the axial width of the torus). This implies that, that the SE (counter-)jet is confined within the torus for long periods of time, during which the bright segment may be the entire SE (counter-)jet of the Vela nebula. The observations also indicate that bright segment is a highly dynamic feature, varying in shape and brightness on a timescale of 1-2 weeks [20]. We note that this variability is quite expected in our RMHD model, where this segment develops surrounded by two oppositely rotating vortices – the in-funnel eddy and the reverberating circulation flow.

The third segment – outer extension – begins where the nearly choked counter-jet breaks through the convergent circulation flow and enters the nebula’s tail. The tail is composed of the $e^{\pm}$ plasma being pulled by the stream from the nebula, mostly from its lee hemisphere. When a narrowly collimated counter-jet is injected into the co-directional flow in the tail, it gradually disperses, and its emission fades out. The outer extension of the SE jet of the Vela PWN is indeed very dim. It is $\sim 7$ times dimmer than the outer extension of the NW jet [19]. Yet, it is still distinguishable even in the individual frames (figure 2) as a very diffuse, gradually expanding, outflow with brightened blobs at its spine. The blobs are numerous and clearly visible in some frames but are rare and barely noticeable in the others, as if the outflow of the jet was somehow modulated or temporarily blocked at the point of exit from the leeward torus.

Figure 2: The 0.5-8 keV Chandra images (PI: G.G. Pavlov) that show the structure and evolution of the outer extension of the SE jet of the Vela PWN. The black cross marks the position of the Vela pulsar. The observations IDs and dates are shown on the left. The color scale is adjusted to highlight blobs within the spine of the outer extension of the SE jet.

### 3.3. The stream misaligned with the PWN axis: implications on the jet and the counter-jet.

To model a PWN in the stream, which makes an angle of $\sim 60^\circ$ with the PWN axis, as in the Vela PWN, 3D simulations are required. It remains to be seen, in particular, whether the helical bending of the windward (NW) jet in Vela [19, 7] is caused primarily by the stream, or by the kink instability, or by the combination of both.

One could speculate on how a misaligned stream would affect the jets. Obviously, their shapes and dynamics will change depending on the strength and the angle of the incident stream. At the same time, their inner (sheltered by tori) and outer (protruding from the tori) sections will each change in their own way.

The outer extensions, interacting with a stream directly, will bend in the stream’s direction and stretch further, similar to how a fountain behaves in a strong oblique wind. The windward extension will probably show a kind of reverberations due to the jet’s inertia. The lee extension, when joining a misaligned stream (all other things being equal), will degrade slower than in a co-directional stream, and hence can be traced for further distances from the pulsar.
The inner segments will be affected to a lesser extent. A misaligned stream will not penetratet that deep into the windward hemisphere, so, all other things being equal, the windward inner section will appear longer. The lee inner section will still interact with the stream through the lee torus. The back side of this torus, which meets the stream later, will rebound with a lag in relation to its front side, so the circulation flows from the front and back sides will converge incoherently toward the axis, forcing the tip of the inner section to wag like a dog’s tail.

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Appendix. Parameters of the simulation.

The 2.5D RMHD model of a PWN is built with the PLUTO code [15], on a spherical grid. The coarse grid includes 96 logarithmically spaced radial bins, from \( r_{\text{min}} = 2 \cdot 10^{-4} \) l.y. to \( r_{\text{max}} = 3.13 \) l.y., and 32 polar angle \( \theta \) bins. Until the age of 6 years, the PWN evolves on the coarse grid. This introduces high numerical viscosity that quenches the small-scale stochastic vorticity that destroys persistent structures in the nebula [20]. At \( t = 6 \) yr, the 2-level adaptive mesh refinement is activated. The model nebula has a high inclination, \( \alpha = 80^\circ \), and hence a wide equatorial belt of low magnetization (as likely the case for the Vela nebula, whose inclination, however, is not known for certain). The model also suggests that the pulsar wind is weakly magnetized, \( \sigma_0 = 0.1 \), to dampen the shock dynamics [22]. The synthetic X-ray map is produced and the pulsar wind is prescribed following the recipes from previous studies, e.g, [6, 22, 3].

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