Slow motion pulsar wind nebulae

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Abstract. We show that even the slow (subsonic) motion of pulsar wind nebulae (PWNe) relative to an ambient matter has a significant impact on their observables. The motion changes the appearance of nebulae on X-ray images, comparing to what would be observed for a nebula at rest. Accounting for the relative motion is necessary to avoid misinterpretation of the structure of the nebulae when analyzing their X-ray morphology. The motion also introduces some extra time scales in variability of non-thermal high-energy emission of PWNe and allows to reproduce a number of their structures that are not explained by stationary nebula models.

1. Introduction

Pulsar wind nebulae (PWNe) are natural labs for studying magnetized relativistic plasma. The dynamics of magnetized flows can be studied by matching fine-resolution observational maps of high-energy non-thermal radiation from PWNe with the results of relativistic magnetohydrodynamic (RMHD) modelling. The RMHD models typically consider nebulae at rest, unless the bow shock nebulae of supersonically moving pulsars are studied. While very successful in interpreting the general X-ray morphology of PWNe, these models are overly turbulent and run into problems in reproducing fairly stationary PWN structures, such as the inner ring in the Crab Nebula or the double torus in the Vela PWN. In what follows we show that taking into account even the slow (subsonic) motion of an ambient matter in the pulsar’s rest frame can strongly affect the simulated PWN morphology and be important for the correct implications on the pulsar wind parameters and PWN type. It allows to reproduce a number of structures, absent or reproduced with a certain stretch in models with pulsar at rest, and provides some results on the variability of the PWN structure, being of interest due to observations of the variability of the Crab nebula in X-rays and γ-rays [7, 10, 17, 19].

2. Results

2.1. X-ray appearance of PWNe versus pulsar motion

Figure 1 illustrates how the motion of the pulsar affects the appearance of its nebula in the X-rays. The same RMHD model of the PWN ($\alpha = 45^\circ$, $\sigma_0 = 0.03$) is presented in all panels of the figure. On the synthetic X-ray maps, it is shown under the aspect of how the Crab and Vela nebulae are seen from Earth (see details in figure 2). The pulsar (with a magnetic inclination $\alpha$ and an initial wind magnetization $\sigma_0$) moves relative to the surroundings at a subsonic velocity, translating to Mach number $M_s = 0.7$. The direction of this motion is opposite in the top and the bottom rows in the figure. In the top row, the velocity points in the direction of the...
The southeastern axis (SE) of the nebula, while in the bottom – in the direction of its northwestern axis (NW). To give an idea of the dynamics of the nebula, each of these cases is illustrated with two snapshots taken 2 years apart (left and middle panels in each row).

The difference in the X-ray morphology between the top and the bottom maps is remarkable. In the bottom row, the bright X-ray features are represented by the NW jet and two closely-spaced, diffuse, steady-state arcs. These arcs are much more intense than the main torus, so that the model resembles in morphology the Vela nebula. Vela is an archetype of double-torus nebulae; its X-ray image is shown to the right. There one can see two regular arcs, which highlight the Doppler brightened parts of two regular tori, and a bright NW (headward) jet.

In the top row, the morphology is drastically different, since the bright features originate from the other regions of the nebula. Within the main torus, one can discern a bright steady-state ring, one or two transient arcs, and the SE jet. This X-ray map has much in common with the X-ray image of the Crab nebula, an archetype of single-torus objects, shown to the right. In particular, the bright ring is \(\sim 3\) times smaller than the main torus and has almost uniform brightness along its perimeter like the ‘inner ring’ in Crab (the bright ring, surrounding the under-luminous region hosting the pulsar, is attributed to the wind termination shock). The main torus, like the torus in Crab, comprises ‘wisps’ – thin transient arcuate sub-structures with a slightly increased synchrotron intensity. Finally, the SE jet, like the corresponding jet in Crab, originates in a certain diffuse sub-structure, adjacent to the polar section of the bright central ring. In the literature this sub-structure is commonly referred to as ‘Sprite’ or ‘Anvil’ [6].

It is noteworthy, that in both cases, only the headward jet of the nebula is visible on the X-ray maps. This jet is bold and bright, and quite dynamic, as can be guessed by comparing the snapshots taken 2 years apart. The opposite, rearward jet is either much fainter, as in the bottom row, or just invisible, as in the top. In its place, in both cases one can discern a faint and fuzzy structure, trailing behind the nebula. This tail is comprised of the magnetized \(e^\pm\) plasma, pulled out of the nebula by the incoming stream of the surrounding matter.

Thus, in its subsonic motion, the PWN can conditionally exhibit morphological characteristics of either double-torus or single-torus object, depending on the projection of its velocity onto the line of sight of the observer. This effect is important at interpreting the type of PWNe (single-torus or double-torus?), whose structure has not yet been resolved with such a fine spatial resolution as in Crab and Vela. The integral X-ray flux from our PWN model is also projection dependent and is \(\sim (10–15)\%\) higher when the nebula is viewed from the rear side.

The other characteristic feature of the moving nebulae (with a low-magnetized wind) is the striking dissimilarity of their headward and rearward jets (see details in [15]). Only the headward jet is bright and prominent on the X-ray maps, while the rear jet is either dim or invisible, and submerged by (or wrapped in) a dim and diffuse structure, trailing behind the nebula in a jet-like manner. Interestingly, a similar behaviour is observed in the jets of Crab and Vela: one of them is bright, bold and dynamic, while the opposite is either dim for most of its length (in Vela) or invisible (in Crab), but enshrouded in a dim and diffuse structure that only distantly resembles a jet-like outflow. The bright SE jet in Crab is clearly visible on X-ray images; it indeed shows no serious variations in brightness until it bends and terminates at \(1\)′ from the pulsar [18]. The same is applied to the base (called the “inner jet” in [13]) of the headward NW jet in Vela that appears as a steadily and homogeneously bright feature in the \(10''\) gap between Vela’s arcs [13].

Finally, we would like to stress that RMHD models of moving nebulae can easily reproduce the ‘Sprite’ and ‘inner ring’ features that are present in X-ray images of the Crab nebula, but are absent or reproduced with some reservations in synthetic X-ray maps of RMHD models of nebulae at rest (e.g., [2] [16]). This again indicates the importance of taking into account the motion of the pulsar (or/and of the surrounding matter) while interpreting of the observed X-ray images of PWNe.
Figure 1: Four panels on the left: maps of synthetic synchrotron X-ray emission of a model PWN ($\alpha = 45^\circ , \sigma_0 = 0.03$); the snapshots are taken at $t = 12$ yr and 14 yr. The model is shown under the aspect of how the Crab and Vela nebulae are seen from Earth – the PWN axis is tilted $\sim 120^\circ$ to the line of sight and $\sim 130^\circ$ to the north (upward in this figure). In all 4 maps, the brightness is linearly color-coded in arbitrary units. The red arrows show the direction of the subsonic (with Mach number 0.7) pulsar’s motion relative to the ambient medium ($\rho_{\text{amb}} = 10^{-26}$ g · cm$^{-3}$). The maps are compared to the Chandra X-ray maps of the Crab [8] and Vela nebulae (top and bottom panels on the right).

2.2. Time variability of PWNe versus pulsar motion
Let us now illustrate the effect, which the motion of pulsars may have on variations of X-ray morphology of their nebulae. These variations, most likely, lay behind the variations in brightness (intensity) of high-energy non-thermal emission of PWNe. Both types of variations – in morphology and in high-energy emission – are seen in Crab and Vela, two nearby nebulae, which have been monitored for decades (e.g., [7, 10, 11, 12, 13, 14, 15, 16, 17]). Note, however, that the spectrum of electrons emitting in X-rays is fixed in our models (we used the simulations of the spectrum produced by relativistic shock [11]); therefore, the change in efficiency of their production due to structural variations is not taken into account.

It is clear that the time scale of morphological changes depends on the overall size of the compact X-ray nebula (that is, on the spin-down luminosity of the pulsar). Say, Vela, being $\sim 7$ times smaller than Crab, might change its overall structure much faster. Insolfer as individual PWN features are considered (jets, torus, shock structures, etc.), it would make sense to distinguish between two causes of their variability – a change in their spatial position, and their inner changes – because these two contributions may have different time scales. Such a distinction, however, is not always possible given the complex morphology and non-linear coupling of plasma outflows in PWNe. The structure of these outflows determines the time
scales of variations in individual features of a nebula. The structure, in turn, depends on the inclination of the pulsar ($\alpha$), on the initial magnetization of the pulsar wind ($\sigma_0$), and on the (local collisionless) viscosity of strongly magnetized $e^\pm$ plasma. The properties of the ambient matter are also important, including its density and the relative velocity. For instance, in strongly magnetized nebulae, the flows are more dynamic, since the magnetic field promotes variability [16]. A denser external medium, on the other hand, can dampen variability. As for a relative speed of nebulae, its effect on variability is described below.

We illustrate this effect by taking the cusps of the termination shock as an example. Cusps – points of the shock working surface, closest to the pulsar, located where this surface intersects with the PWN axis, dives toward the pulsar and forms a kind of funnel (the black contour in figure 4). In figure 2, the offset of the cusps from the pulsar position is traced for two decades. To maximize the effect, the problem setup is taken as follows. An axially elongated PWN model [14] is employed, in which the outflows from the opposite hemispheres do not mix with each other. This model represents a double-torus (Vela-like) nebula, which can form around a pulsar with high inclination and low-magnetized wind (here we take $\alpha = 80^\circ$ and $\sigma_0 = 0.03$–0.1). The PWN is further immersed into a low-density surroundings. Before the PWN is let evolve, the ambient matter is set into motion in the entire computation domain. Again, to maximize the effect, the motion of this stream is taken to be transonic (which may be treated as the upper limit for slowly moving nebulae). Long story short, the double-torus PWN expands in a free low-density stream with a Mach number of 1.3. The axis of the nebula is aligned with the stream, so that the headward jet pushes against the stream, while the rear one goes along. Such a setup resembles the case of Vela – the double-torus nebula that encounters a transonic stream of Mach number 1.3, induced by the passage of the reverse shock of the supernova (e.g., [3]).

According to figure 2, in the moving PWN, the two cusps differ drastically in their dynamics. The headward cusp shows a barely noticeable periodicity, whereas the rear cusp runs into intense oscillations. Comparing two panels of the figure, one can conclude that the swing and the period of oscillations are larger in the more magnetized nebula. As the nebula expands, the oscillation period gets longer and absolute amplitude increases. In the more magnetized nebula, the rear cusp can change its offset from the pulsar 2–3 times within 2–3 years. Note, that the oncoming stream makes the nebula even more elongated with time (in its axial cross section), since the average offset of the rear cusp increases faster than that of the opposite cusp.

The PWN outflows show both long-term and short-term quasiperiodicity in their dynamics and appearance. The long-term variations are set by the reverberations of the tori in the free stream (which is steady and homogeneous in our model) and determined by the period

Figure 2: Oscillations of the positions of the headward (blue curve) and rearward (red curve) cusps of the wind termination shock in transonic double-torus PWN models moving with Mach number $M_s = 1.3$ relative to the surroundings ($\rho_{amb} = 10^{-28}$ g cm$^{-3}$). The pulsar inclination and initial wind magnetization are ($80^\circ$; 0.03) and ($80^\circ$; 0.1) on the left and right plots, respectively.
of a revolution of the reverse circulation flow in the rear hemisphere of the PWN (this period increases as the PWN expands and the tori grow in size). The shorter times scales can be related to other quasiperiodic patternings, e.g., to the small persistent magnetic vortex, which forms within the rear funnel of the shock, to the pulsations in the equatorial outflow, to jets instabilities, etc. Despite the fact that the change in the X-ray flux from individual features can be significant, the integral X-ray flux from the PWN changes by no more than 1.5% in the course of quasiperiodic variations in its structure. Changes in the high-energy flux may be more pronounced, given the short-term but strong variability observed in highly magnetized compact areas – inside the shock funnels or just outside the Mach belt.

In figure 3 left panel, we show time evolution of the offsets of the cusps in a single-torus (Crab-like) PWN model, whose synthetic X-ray maps are shown in Fig. 1 ($\alpha = 45^\circ$, $\sigma_0 = 0.03$, $\rho_{amb} = 10^{-26}$ g · cm$^{-3}$). In this model, the highly-magnetic post-shock outflows, streaming along the arched sections of the shock in the opposite hemispheres of the nebula, converge and interwine with each other in the equatorial region. Because of this mixing, structures in the opposite hemispheres can no longer evolve independently. This also applies to the cusps. They now oscillate in position much more coherently than in a double-torus nebula, which lacks such mixing.

Next to the cusps, in figure 3 we show the trend and fluctuations of the magnetic field strength in the post-shock area, where the strong magnetic outflows meet each other for the first time. This region is marked with a rectangle in figure 4 on the magnetic map of the nebula on the right. As can be seen, the field varies on the same time scales as the offsets of the cusps (\(\sim 0.4\)–\(0.6\) yr). With some variations, the field doubles its strength in a couple of months, and for some it becomes almost twice as weak. As the nebula expands, the average field strength gradually decreases, but not the amplitude of its fluctuations, which become even stronger.

In summary, even a slow (subsonic) motion of a pulsar relative to an ambient matter strongly affects its synchrotron nebula – its structure, X-ray morphology, dynamics and, hence, the time-scales of variations in its non-thermal high-energy radiation. New structures can form (an in-funnel vortex, an inner ring, a Sprite, an $e^\pm$ tail, etc.), new dynamics sets in (reverberations, etc.), and new time scales emerge when the oncoming stream begins to act as a driving force.

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Appendix. Numerical model

Our axisymmetric 2.5D runs make use of RMHD module of the PLUTO code [9]. The basic computational grid is spherical, with 32 polar angle bins and 96 log-spaced radial bins from 0.0002 to 3.13 light years (ly). Adaptive Mesh Refinement with 2 levels is used. Between the levels, the cell sizes differ by a factor of 2, in each coordinate. The activation of the adaptive grid was postponed until the moment \( t = 6 \) years, to introduce an additional numerical viscosity (dissipation). This effectively damps an excessive vorticity, which develops in ideal high-resolution RMHD models and does not allow the steady-state structures to form in a PWN [14]. The recipe for calculating synthetic X-ray emission and the pulsar wind settings are the same as in, e.g., [14] [10] [1]. All results and illustrations in the paper are presented for the PWNe in a self-similar expansion stage.

\[ M = 1.3, \alpha = 80^\circ, \sigma_0 = 0.03 \quad M = 0.7, \alpha = 45^\circ, \sigma_0 = 0.03 \]

\[ \text{Figure 4: Azimuthal magnetic field (in } \mu \text{G)} \text{ in a transonic double-torus (left panel) and a subsonic (right panel) PWNe. The termination shock (TS) is outlined by black contours. Small black boxes next to the TS contour on the right map show the regions where a mean magnetic field was calculated. Red arrows show the direction of pulsar’s motion relative to the ambient medium. Black arrows show the line of sight direction (} \theta \text{view} = 120^\circ) \]

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