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Escape of particles from pulsar bow shock nebulae

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Abstract. An increasing number of evolved pulsar wind nebulae have been observed in the last years to show extended X-ray features, apparently developing close to the pulsar location and defying expectations from canonical MHD models, being strongly misaligned respect to the pulsar direction of motion, asymmetric and collimated up to long distances from the parent nebula. Extremely extended TeV halos have also been observed surrounding old pulsar wind nebulae, requiring the presence of high energy particles diffused around the source. Moreover pulsar wind nebulae are candidate to be primary sources, in contrast to dark matter models, of the positron excess revealed by different instruments in the cosmic ray spectrum and are then expected to replenish the ISM with electrons and positrons.
It was suggested that particles can efficiently escape from those systems, with some degree of charge separation, and produce the observed signatures. With the present project we have investigated this possibility and show that, not only particles are able to efficiently stream out from evolved pulsar wind nebulae, but that the outflow can easily be asymmetric and charge separated, accounting for the observed features.

Key words. ISM: supernova remnants – ISM: cosmic rays – magnetic fields – MHD – methods: numerical – pulsars: general

1. Introduction

The present project (INA17_C4A31 – 3 millions of cpu hours) is the follow up of the previous class A one *"Three-dimensional relativistic MHD simulations of bow shock nebulae"*, in which we have investigated the dynamics, geometry and emitting properties of bow shock pulsar wind nebulae within a wide range of different physical configurations. Its feasibility was ensured by the MoU INAF–CINECA agreement, that allowed for an easy submission and fast evaluation of the project, assuring the continuity of numerical operations.

Pulsar wind nebulae are powered by a rotating neutron star (the pulsar), left as debris of a supernova explosion. The pulsar loses rotational energy in the form of a relativistic, magnetized and cold wind, mostly (if not completely) made of electrons and positrons. The interaction of that wind with the slowly expanding supernova remnant induces the formation of a termination shock that slows down and heat up the wind. The shocked wind becomes visibile through non-thermal emission that forms a fill-centered pulsar wind nebula (PWN), shining at a broad range of wavelengths.

In the late phase of their evolution PWNe generally escape from the bubble of their parent supernova remnant and interact directly with the interstellar medium (ISM). Since the distribution of pulsar kick velocities at birth peaks around 350 km/s, with speeds up to $\sim$ 700 km/s (Faucher-Giguère & Kaspi 2006), their motion is supersonic in the ISM (where $c_s \sim 10 - 100$ km/s). This induces the formation of a bow shock (BS) around the PWN, reshaping it into a cometary-like nebula, with the pulsar at the bright head followed by a long tail of plasma developed in the direction opposite to the pulsar motion. These systems are known as bow shock pulsar wind nebulae (BSPWNe). In the last years intriguing features have been observed surrounding BSPWNe: γ-ray halos extending around the pulsar location (Abeysekara et al. 2017; Posselt et al. 2017), X-ray *prongs* or *whiskers* arising close to the BS head (Temim et al. 2015; Klingler et al. 2016; Kargaltsev et al. 2017; Kim et al. 2020) and puzzling one-sided jets highly misaligned with respect to the pulsar direction of motion (Hui & Becker 2007; Pavan et al. 2014; Klingler et al. 2020; de Vries & Romani 2020).

In Bandiera (2008) it was suggested, for the first time, that the misaligned powerful X-ray jet observed in the Guitar nebula might be the indication of an efficient escape of high energy particles, close to the pulsar voltage, streaming outside from the BS head along the ISM magnetic field lines. Aim of this project is to investigate, for the first time with 3D relativistic MHD numerical simulations, this possibility and the physical mechanism for the particles to escape into the ISM field, accounting for the formation of the observed features.

2. Simulations and results

Simulations have been performed using the PLUTO code with the Adaptive Mesh Refinement (AMR) facility to get the requested resolution along the grid (Mignone et al. 2007, 2012). The base grid has 128^3 equally spaced grid points, with 4 AMR levels to reach the maximum equivalent resolution of 2048^3 cells. An extended discussion of the numerical scheme and analysis performed on the simulations can be found in Olmi & Bucciantini (2019a,c).

The initial properties of the pulsar wind (mutual inclination of the magnetic field and spin axes, magnetization and distribution of the energy in the wind) have been defined as the most suitable to produce an asymmetric escape as from the studies presented in Olmi & Bucciantini (2019a,b), where no magnetic field was considered in the ambient medium. For the present study we have simulated the selected configurations with the addition of a uniform magnetic field in the ISM, defined as to lay in the same plane of the pulsar kick velocity and spin axis and with strength $B_{\rm ISM} = (0.01\rho_{\rm ISM}v_{\rm PSR}^2)^{1/2}$ (where $\rho_{\rm ISM}$ is the mass density of the ISM and $v_{\rm PSR}$ the pulsar kick velocity). Particles trajectories have been then added using an explicit Boris Pushing technique (Boris & Shanny 1972; Vay 2008; Higuera & Cary 2017), on top of the dynamical configuration evolved with the numerical MHD simulation. The electric field is obtained from the ideal MHD condition $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, where $\mathbf{V}$ is the flow speed and $\mathbf{B}$ the magnetic field. Particles are injected with different charge (electrons and positrons) and energy, namely $E_{e^\pm} = [0.5, 1.0, 3.0, 10] \times 10^7 m_e c^2$, with m_e the mass of the electron and c the speed of light. Geometrical properties of the escape process have been constrained by considering the particles injected at different sectors of the termination shock of the wind.

We found that in general particles coming from the frontal polar region of the pulsar wind can escape more efficiently than others, that on the contrary tend to remain confined in the BSPWN tail. A transition in the properties of the escaping flow appears with increasing the particles energy $E_{e^\pm}$. Low energy particles escape from the head of the BSPWN through sporadic magnetic reconnection locations between the nebular and ISM magnetic

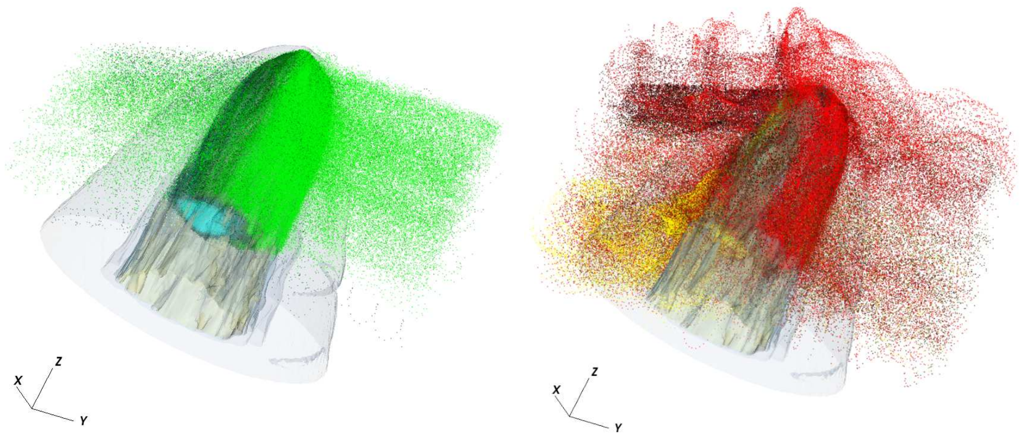

Fig. 1. Three-dimensional maps of the bow shock, shown in grey, and positions of wind electrons and positrons. *Left panel:* electrons of energy $3 \times 10^7 m_e c^2$, with different colors indicating different injection locations in the wind (green: $0° - 60°$; black: $60° - 120°$; cyan: $120 - 180°$). *Right panel:* positrons of energy $10^8 m_e c^2$ that escape almost diffusively (red: $0° - 60°$; black: $60° - 120°$; yellow: $120 - 180°$). For additional details please see Olmi & Bucciantini (2019c).

fields, that form at the magnetopause (as also suggested by Barkov et al. 2019). The escaping outflow is highly asymmetric, reflecting the asymmetry of the selected configuration (see Fig. (1) of Olmi & Bucciantini 2019c for a clear representation). In this case the outflow appears almost not charge separated.

On the other hand the outflow becomes more and more charge separated when increasing the particles energy, with the escape process becoming diffusive.

The appearance of different features around evolved PWNe can be then explained as the footprint of the same process: the efficient escape of particles from the BS boundary into the ISM. Diverse formations then arise as the effect of the different energy of the escaping particles and their interaction with the ambient magnetic field.

As an example in Fig. 1 we show the formation of a one-sided jet (left-hand panel), very similar to what observed in the Guitar and Lighthouse nebulae, and the transition to the diffusive regime while increasing the particles energy (right-hand panel).

Our findings also show that $\gamma-$ray halos, as the famous TeV halo surrounding the Geminga pulsar, may arise from the efficient (diffusive) escape of high energy particles from the BS boundary.

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