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A DECADE OF AGILE

The Crab nebula in the light of three-dimensional relativistic MHD simulations

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Abstract
Pulsar wind nebulae inside young supernova remnants, and in particular the Crab nebula, are probably the best laboratories for high-energy astrophysics and relativistic plasma physics. They have been modeled numerically for more than a decade through multi-dimensional relativistic MHD simulations, relying on axial symmetry until a few years ago while currently using full three-dimensional simulations employing adaptive meshes. Here, we discuss the most recent findings, especially those obtained by our Arcetri group, focusing on the problem of magnetic field dissipation inside the nebula.

Keywords ISM: supernova remnants · ISM: individual objects · Crab nebula

1 Introduction

Pulsar wind nebulae (PWNe), also known as plerions, are found within Supernova Remnants (SNRs) in the cases, where a still active pulsar is capable to energize their inner regions and make them shine through non-thermal emission at all wavelengths, as it happens for one of the most famous and well-studied objects in the sky, the Crab nebula (Gaensler and Slane 2006; Hester 2008). PWNe are basically bubbles made by relativistically hot (pair) plasma and magnetic fields, created by the confinement of the relativistic wind from the pulsar by the slowly expanding SNR ejected (cold) material. This transition occurs through a termination shock, where particles are accelerated and the magnetic field (mainly toroidal with respect to the pulsar's rotation axis) is amplified, thus leading for the Crab nebula to synchrotron radiation from radio up to gamma rays and to inverse Compton emission at TeV energies and beyond (Rees and Gunn 1974; Kennel and Coroniti 1984a, b; Atoyan and Aharonian 1996).

The discovery of fine structures in the morphology of PWNe in the radio, optical and X-ray bands, namely, polar jets, an equatorial torus striated with rings, and even time-dependent features like knots and wisps (Weisskopf et al. 2000; Hester et al. 2002; Pavlov et al. 2003; Bietenholz et al. 2004), has lead to the necessity of a multi-dimensional theoretical modeling. In particular, the inner jet-torus structure can be reproduced if one supposes an anisotropic pulsar wind with higher energy flux in the equatorial region, so that the termination shock becomes oblate and jets may form by magnetic hoop stresses in the post-shock flow (Lyubarsky 2002). As far as the motion of wisps is concerned, a different origin in latitude for the emitting particles at radio and optical/X-ray bands seems to be required to explain the observations (Schweizer et al. 2013).

Axisymmetric simulations in the regime of relativistic MHD, supplemented with basic prescriptions for synchrotron emission, are able to successfully reproduce the observed jet-torus structure, the appearance of Doppler-boosted knot and arc-like features, and even the motion of wisps (Komissarov and Lyubarsky 2004; Del Zanna et al. 2004, 2006; Camus et al. 2009; Olmi et al. 2015). However, some issues are still unsolved. First, the nature of the radio emitting particles is still debated, as they may be either a relic population, part of the pulsar outflow, or continuously

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re-accelerated in the whole nebula (Olmi et al. 2014). Moreover, two-dimensional simulations only admit limited values of the wind magnetization σ (the ratio of Poynting to particles energy flux), say $\sigma \approx 0.01$–0.1, and it is basically impossible to reach an average magnetic field in the nebula sufficiently high such as to reproduce, at the same time, both the observed synchrotron and the inverse Compton spectral components without invoking unrealistically high numbers of emitting particles (Volpi et al. 2008).

2 Three-dimensional simulations of the Crab nebula

In the last years, the numerical modeling of PWNe, and of the Crab nebula in particular, has finally moved to 3D. Preliminary runs for very limited evolution times ($t \simeq 70$ years, for a nebula's age of a thousand years) have shown how the inner morphology is well reproduced as in 2D runs, especially the size of the termination shock and the polar outflows. Contrary to axisymmetric simulations, this is true even for Poynting-dominated pulsar winds (Porth et al. 2013, 2014). Synchrotron images in the X-rays look reasonable (only jets are too faint), and the bright and variable small-scale features are still present, but unfortunately, spectral information is absent and inverse Compton emission, which is crucial to disentangle the contribution by the magnetic fields and by the particles, has not been worked out.

In Olmi et al. (2016), we have tried to make some improvements in the 3D modeling of the Crab nebula by performing new simulations with the PLUTO code for relativistic MHD adopting Adaptive Mesh Refinement (AMR) techniques (Mignone et al. 2012). The initial setup follows the usual strategies also adopted in 2D, see Del Zanna and Olmi (2017) for details, and the simulation is performed using a $[-10\ \mathrm{ly}, +10\ \mathrm{ly}]^3$ grid, with the wind being continuously injected in a sphere of $r = 0.01$ ly. Unfortunately, the wind injection is very delicate and seven levels of AMR are required to resolve the inner part leaving sufficient resolution also near the external contact discontinuity. The computation is then extremely expensive; nonetheless, we have managed to reach $t = 250$ years, well within the self-similar expansion phase, for a nebular radius of $r \simeq 2$ ly.

Here, we would like to concentrate on the structure of the magnetic field and to briefly discuss the role of dissipation within the nebula. The simulation employs a pulsar wind with equipartition toroidal field (the magnetization parameter is $\sigma = 1$) and a narrow striped wind equatorial region with a field of lower strength (we suppose that dissipation has occurred around the current sheet), for an effective latitudinally averaged magnetization of ≈ 1.5. This is sufficient to activate post-shock the Lorentz force stresses, which are due to the still dominant toroidal magnetic field component, and to re-direct the flow towards the polar axis, as can be clearly seen in Fig. 1.

Contrary to axisymmetric simulations, the magnetized jet in our 3D run is clearly unstable due to kink instabilities, as expected theoretically (Begelman 1998) and previously found numerically (Mizuno et al. 2011; Mignone et al. 2013; Porth et al. 2014). The mixing and the dissipation of the magnetic field inside the nebula are much stronger than in 2D, and this is the reason why even Poynting-dominated pulsar winds are allowed in 3D simulations and one is allowed to claim that the long-standing σ-paradox has been finally solved (Porth et al. 2013). In Fig. 2, we show the ratio between the poloidal to toroidal magnetic field strength for a meridional cut (the plane $x - z$ with $y = 0$). The toroidal field is still dominant only inside and around the termination shock (red/orange color), while in the polar jets and in the rest of the nebula, the components are randomized by the flow and the situation is much more complex. When the magnetic field is randomized, transport of particles also changes by becoming of diffusive type, rather than just due to advection, and properties of the non-thermal emission can be strongly affected (Tang and Chevalier 2012; Porth et al. 2016).

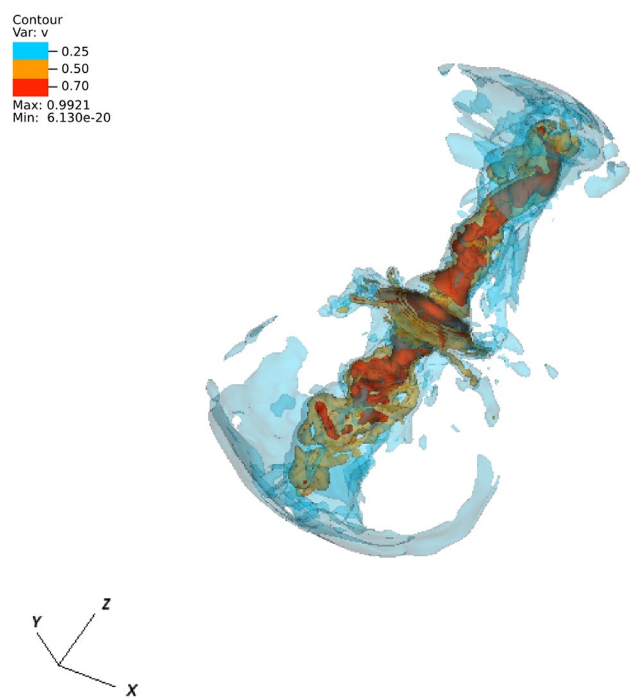

Fig. 1 Rendering of the 3D structure of the relativistic flows inside the nebula. The highest speeds ($v > 0.7c$) are achieved along the surface of the termination shock and, above all, in the polar jets produced by magnetic hoop stresses

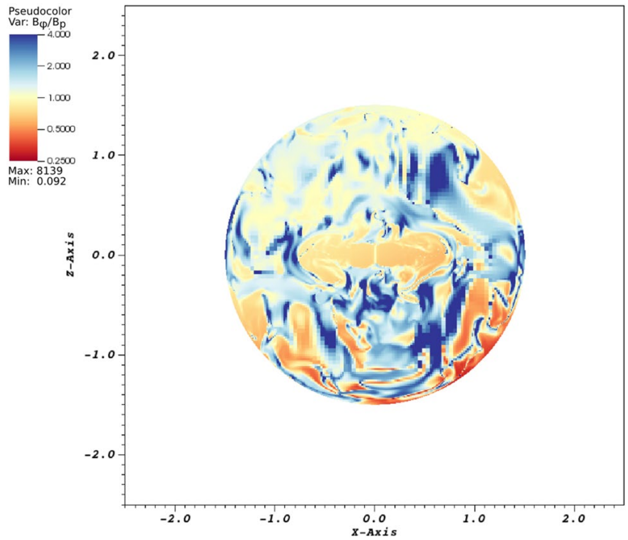

Fig. 2 Magnetic field structure inside the nebula for $y = 0$. The map of $B_{\text{pol}}/B_{\text{tor}}$ is shown, with red/orange colors indicating a dominant toroidal component and blue/cyan colors indicating a stronger poloidal one

3 Future work

The results by our group based in Arcetri highlighted above are certainly promising, but we are still far from a completely satisfactory 3D simulation of the Crab nebula. The simulation time is still limited compared to the real age, though the self-similar expansion phase has been reached. In spite of an injected $\sigma \sim 1$ pulsar wind, the average magnetic field inside the nebula is only half of that one inferred from observations ($\simeq 200$ μG), so that emission properties cannot be fully accounted for. Moreover, the effects of synchrotron and adiabatic cooling on particles are taken into account using simple tracers advected by the flow. However, these are subject to unphysically high dissipation in the external regions of the nebula, where turbulent motions and high-density material entrainment from the supernova ejecta are present. We are planning for future simulations to use the recently updated version of the PLUTO code with particle-in-cell (PIC) and Lagrangian macroparticles (Mignone et al. 2018). In addition, some sort of sub-grid modeling to take into account the effect of turbulence in the synchrotron emission properties, especially polarization, should also be adopted (Bucciantini et al. 2017).

Finally, a very important aspect would be the treatment of magnetic reconnection, which is only numerical in the present simulations in the ideal MHD regime, either by the ordered fields near the termination shock or inside the jet, as well as in the outer nebular turbulent regions. This is crucial to properly assess the rate of magnetic field dissipation, but it is also the best candidate mechanism to explain the stochastic gamma-ray flares observed in the Crab nebula (AGILE-coll 2011; FERMI-coll 2011). Models for efficient relativistic reconnection have been recently proposed and they have been applied to the physical environment of the Crab nebula (Cerutti et al. 2014; Del Zanna et al. 2016; Lyutikov et al. 2018), though fully consistent simulations of PWNe employing resistive relativistic MHD are still missing.

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