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2D Relativistic MHD Simulations of PWNe: Preliminary Results

Elena Amato

INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5, I-50125, Firenze, Italy

Luca Del Zanna, Niccolò Bucciantini

Dipartimento di Astronomia e Scienza dello Spazio, Università di Firenze, Largo E. Fermi, 2, I-50125, Firenze, Italy

Abstract. We present preliminary results of 2D axisymmetric relativistic MHD simulations of PWNe, aimed at investigating whether structures such as the rings and jets revealed by high resolution X-ray imaging can be due to anisotropy of the outflow from the pulsar. We confirm that these features can qualitatively be explained when the energy flux is larger in the equatorial plane than along the spin axis. Detailed comparison between simulation results and observations is required to constrain the wind energy distribution upstream of the termination shock.

1. Introduction

A growing number of plerions imaged with *Chandra* are found to show in X-rays spatial features such as rings and jets. The latter are especially intriguing and their interpretation poses some theoretical difficulties. These jets, in fact, seem to originate from the very close vicinity of the central neutron star, at a much shorter distance than that at which the shock in the equatorial part of the flow is observed. Due to the theoretical difficulties in explaining self-collimation of a highly relativistic flow (Lyubarsky & Eichler 2002), it has been recently proposed (Bogovalov & Khangoulian 2002; Lyubarsky 2002) that collimation is actually taking place behind the pulsar wind termination shock, where the flow is only mildly relativistic or non-relativistic. This requires that some latitude dependence of the flow energy causes the shock to be much closer to the pulsar along the rotation axis than in the equatorial plane. Here we show preliminary results concerning the dependence of the post-shock flow structure on the upstream wind energy distribution.

2. Pulsar Wind Model and Simulation Set-up

The structure of the wind upstream of the shock is taken as follows. The wind is cold and its Lorentz factor γ is higher in the equatorial plane than at the poles: $\gamma(\theta) = \gamma_0[\alpha + (1-\alpha)\sin^2\theta]$, where θ is the polar angle, the subscript 0 refers to quantities in the equatorial plane, and $\alpha < 1$ parametrizes the anisotropy of the flow. The matter flux is assumed isotropic: $\rho(r,\theta) = \rho_0(r_0/r)^2(\gamma_0/\gamma(\theta))$; and the magnetic field is: $B_\phi(r,\theta) = \sqrt{4\pi\rho_0 c^2\gamma_0^2\sigma_0}\,(r_0/r)\sin\theta$, where σ is the magnetization parameter. The pulsar wind region is surrounded by freely expanding SN ejecta with a constant density profile. The dependence on polar angle of the wind energy flux turns out to be $F \propto \alpha + (1-\alpha+\sigma_0)\sin^2\theta$, very similar to that assumed by Komissarov & Lyubarsky (2003), despite the different assumptions on the magnetic field structure and on the matter flux.

3. Simulation Results

For our simulations we used the relativistic MHD code developed by Del Zanna, Bucciantini & Londrillo (2003). We compared the results of four different simulations performed by varying the values of the parameters α and σ_0: (a) $\alpha = 0.5$, $\sigma_0 = 10^{-4}$; (b) $\alpha = 0.5$, $\sigma_0 = 3\times10^{-3}$; (c) $\alpha = 0.1$, $\sigma_0 = 10^{-4}$; (d) $\alpha = 0.1$, $\sigma_0 = 3\times10^{-3}$. In all cases, $\gamma_0 = 100$. Our results are summarized in the following.

Shape of the termination shock-front. We found that a good approximation to the asymptotic shape of the shock-front is: $R(\theta) = r_s\sqrt{F(r_s,\theta)/F(r_s,\pi/2)}$, with R the spherical radius and r_s the shock position in the equatorial plane.

Shape of the nebula. We confirm the results by Begelman & Li (1992) and van der Swaluw (2003) concerning the elongation of the nebula as a function of the wind magnetization. We also find that the elongation is basically independent of α.

Magnetic energy distribution. With increasing anisotropy the field is increasingly compressed around the equatorial plane and towards the polar axis.

Formation of polar jets. A polar outflow is only found in the cases when $\alpha = 0.1$ and its velocity increases with σ_0. For the parameter space that has been investigated here the maximum velocity observed for the outflow is $v_{\rm jet} \approx 0.15\,c$, a value that is low compared to what observed for Crab and Vela, for which $v_{\rm jet} \approx 0.6\,c$. Values of $v_{\rm jet}$ close to those observed are found, however, in simulations with higher values of σ_0, currently in progress (Del Zanna, Amato & Bucciantini, in preparation).

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