Mem. S.A.It. Vol. 78, 662

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Synchrotron emission simulated maps: Pulsar Wind Nebulae

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Abstract. We show a complete set of diagnostic tools aimed at reproducing synthetic synchrotron emissivity, polarization and spectral index simulated maps in comparison to observations. A numerical shock capturing code is used to evolve relativistic MHD and emitting particle maximum energy equations in time and space. We apply the method to Pulsar Wind Nebulae.

Key words. Supernovae: general; Pulsar: general; Stars:neutron; Radiation mechanism: non-thermal; Relativity; *Magnetohydrodynamics*(MHD)

1. Introduction

Optical and X-ray observations from space (HST and Chandra) show a jet-torus structure in Pulsar Wind Nebulae, (PWNe, a class of Supernova Remnants, SNR, e.g. Vela and Crab Nebula) due to non-thermal synchrotron and Inverse Compton emission at all wavelenghts. To interpret the jet-torus morphology 2-D theoretical models are necessary (Bogovalov and Khangoulian 2002; Lyubarsky 2002). The basic idea is: an anisotropic energy flux (stronger at the equator) creates torus and termination shock (TS) oblate shape; jets are collimated downwards TS (where flux is only mildly relativistic) from magnetic hoop stresses and appear to originate from the pulsar because of the cusp in TS. Only with developments of shock-capturing RMHD numerical scheme (Komissarov 1999; Del Zanna & Bucciantini 2002; Del Zanna et al. 2003) has been possible to solve hyperbolic equations and confirm theories about jet-torus structure.

2. The synchrotron emission diagnostic tools.

Our model (Del Zanna et al. 2004) uses ideal 2-D (axisymmetry) RMHD equations and equation of the maximum particle energy in conservative form (which takes in account of adiabatic and synchrotron losses). These equations are evolved in time and space using Del Zanna's code (recently extended to GRMHD and named ECHO, Eulerian Conservative High Order Scheme, Del Zanna et al. (2007)) in spherical coordinates (r, θ), with a toroidal magnetic field and a poloidal velocity. Initial conditions are: a cold ultrarelativistic wind

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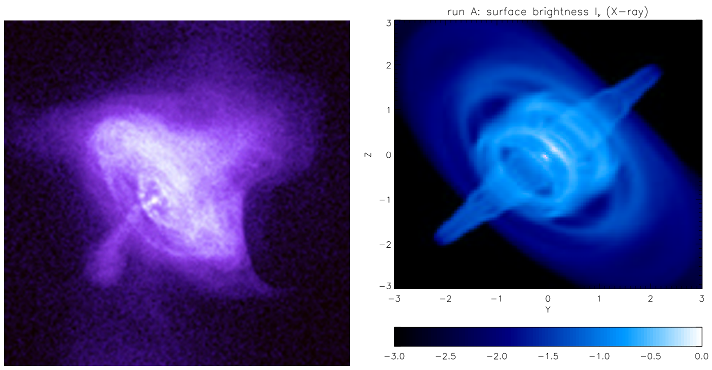

Fig. 1. On the left: Chandra image of Crab Nebula (credit to NASA/CXC/SAO). On the right: simulated brightness map in X-ray band.

(with a Lorentz factor including the energy flux anisotropy) interacting with SNR. We consider a continuos injection of emitting particles at TS with an initial distribution function which is a power-law in energy and isotropic in momentum; the particles are then advected by the nebular mildly relativistic flow. Under the assumption of quasi-stazionarity and of negligible synchrotron losses, the emission coefficient in observer's fixed frame is:

$$j_\nu(\nu, \boldsymbol{n}) \propto D^{a+2} \cdot p \cdot |\boldsymbol{B'} \times \boldsymbol{n}'|^{a+1} \cdot \nu^{-a} \qquad (1)$$

if $\nu_\infty \geq \nu$ and 0 elsewhere. D is the Doppler factor, a is the spectral index, p is the thermal pressure, $\boldsymbol{B}'$ and $\boldsymbol{n}'$ are respectively the magnetic field vector and the direction of the observer in the comoving frame, ν is the optical or X-ray observation frequency, ν_∞ is the cutoff frequency (used to obtain the synchrotron burn-off):

$$\nu_\infty = D \frac{3e}{4\pi mc} |\boldsymbol{B'} \times \boldsymbol{n}'| \epsilon_\infty^2, \qquad (2)$$

where ϵ_∞ is the local maximum particle energy (in units of mc^2).

Integrating the emission coefficient along the line of sight we can obtain surface brightness, optical polarization (Bucciantini et al. 2005) and spectral index maps, (Del Zanna et al. 2006).

The surface brightness ones reproduce the equatorial torus, the two polar jets (even in velocity magnitude), the system of rings, the brighter arch and central knot due to Doppler boosting (see fig.1). The optical and X-ray spectral index maps are very similar to the observed ones (Véron-Cetty & Woltjer 1993; Mori et al. 2004).

After all the present work confirms jet-launching mechanism due to magnetic hoop stresses with the best agreement between simulations and data given by the wind magnetization parameter $\sigma \approx 0.02$.

This complete set for calculating simulated synchrotron emission, polarization and spectral index maps accounting for synchrotron losses can be used for other classes of objects (eg. AGN jets), in any scheme for RMHD (e.g. non-conservative, in full 3-D).

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