INVERSE-COMPTON γ-RAY EMISSION FROM SUPERNOVA REMNANTS EVOLVING IN NON-UNIFORM INTERSTELLAR MAGNETIC FIELDS

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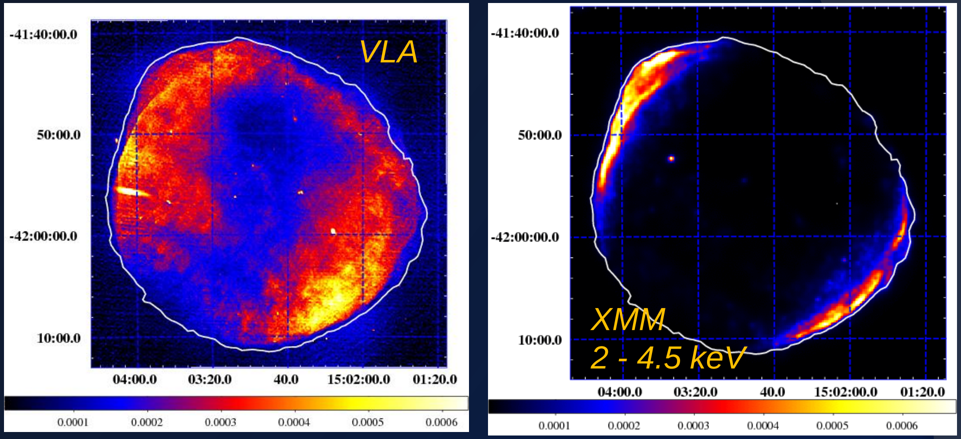
Outline

- Synchrotron and IC emission in BSNRs
- Scope of our project and strategy
  - The MHD model
  - Synthesis of synchrotron and IC emission
- Results
  - The case of SN 1006
- Summary and Conclusions

Synchrotron and IC emission in BSNRs

Observations of SNRs in VHE γ-rays is an important step toward understanding the kinematics of charged particles and B fields in proximity of strong non-relativistic shocks

-> the nature of galactic cosmic rays

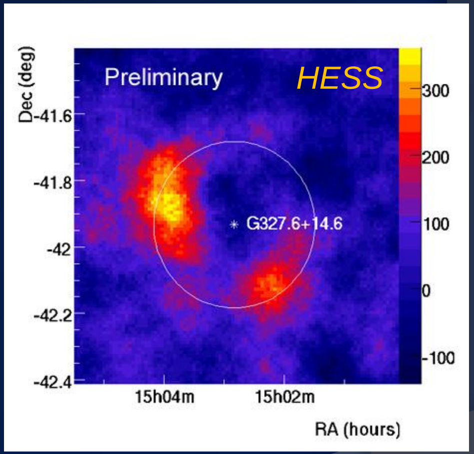


(Petruk et al. 2009)

Important source of information:

- distribution of surface brightness
- comparison with the models

For instance, observed correlations of brightness in radio, X-rays and γ-rays may be considered to favor leptonic scenario (Aharonian et al. 2006; Plaga 2008)



(Naumann-Godo` et al. 2009)

Scope of our project and strategy

Q1: should the patterns of surface brightness in radio, X-rays and γ-rays really correlate if the γ-rays originate from electrons?

Q2: is it possible to derive any constraint for theory when the observed patterns in the three bands are quite similar (e.g. in symmetrical SNRs as SN1006)?

Another key issue for particle kinetics is the 3D morphology of BSNRs

Q3: is it polar-caps or barrel-like?

(Petruk et al. 2009)

Our strategy based on 3D MHD simulations + detailed synthesis of synchrotron and Inverse Compton (IC) emission

→ Detailed comparison of model results with observations

BSNRs: 3D MHD Model

Expansion of a SNR through a non-uniform magnetized medium

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \,,$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} - \mathbf{B}\mathbf{B}) + \nabla P_* = 0 \,,$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [\mathbf{u}(\rho E + P_*) - \mathbf{B}(\mathbf{u} \cdot \mathbf{B})] = 0 \,,$$

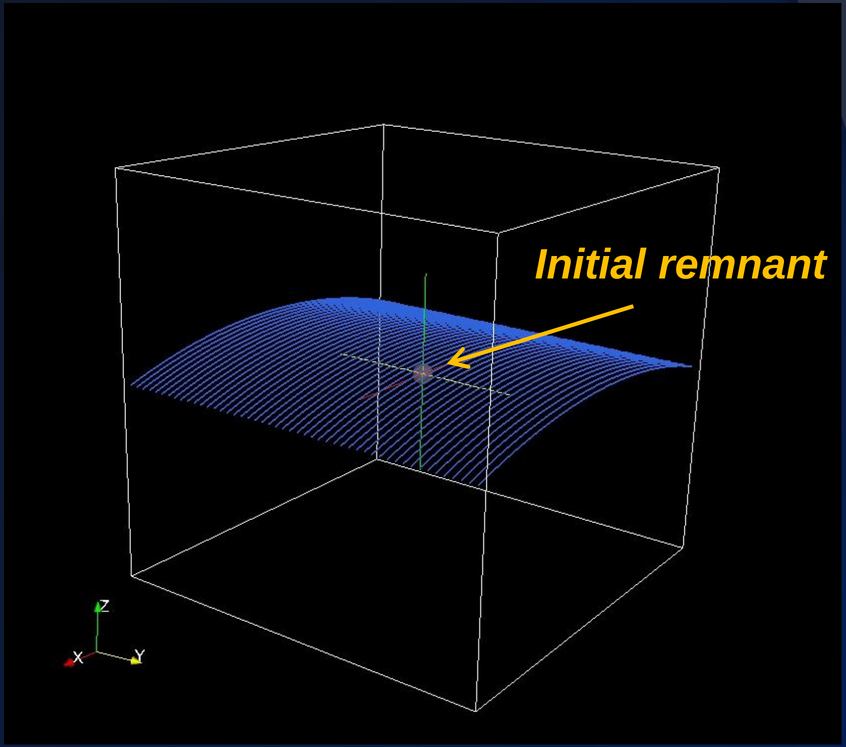
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = 0 \,,$$

where

$$P_* = P + \frac{B^2}{2} \,, \qquad E = \epsilon + \frac{1}{2}|\mathbf{u}|^2 + \frac{1}{2}\frac{|\mathbf{B}|^2}{\rho} \,,$$

γ = 1.1, 4/3, 5/3

FLASH code (Flash center, The University of Chicago)



Only free-expansion phase and adiabatic phase are covered (no radiative phase)

(Orlando et al. 2007)

Synchrotron and Inverse Compton Emission

We follow the approach of Reynolds (1998), generalized to cases of non-uniform ISM and / or non-uniform ISMF

$$N(E) = K E^{-s} \exp\left[-\left(\frac{E}{E_{\rm max}}\right)^{\alpha}\right]$$

$$E_{{\rm max},\xi} \propto f_{{\rm E},\xi}(\Theta_{\rm o})\, V_{\rm sh}^{q_\xi}\, B_{\rm o}^{\lambda_\xi}$$

$$i(\varepsilon) = \int_0^\infty N(E)\,\Lambda(E,\varepsilon)\,dE$$

$$\Lambda_{\rm X}(E,\varepsilon) = \frac{\sqrt{3}e^3\mu_\phi B}{m_{\rm e}c^2}\, F\left(\frac{\varepsilon}{\varepsilon_{\rm c}}\right)$$

$$\Lambda_{\rm IC}(E,\varepsilon) = \frac{2e^4\epsilon_{\rm c}}{\pi\hbar^3c^2}\Gamma^{-2}\mathcal{I}_{\rm ic}(\eta_{\rm c},\eta_0)$$

Energy spectrum of electrons

- K = e^- distribution normalization
- s = slope of e^- distribution, $\alpha < 1$
- E_{max} = max. energy of e^- accelerated by the shock

Models of injection efficiency:

- isotropic, quasi-parallel, quasi-perpendicular

Time and spatial dependence of E_{max}:

- loss-limited, time-limited, escape-limited :

$$E_{max} = \min[E_{max,1}, E_{max,2}, E_{max,3}]$$

Post-shock evolution of e^- distribution accounting for energy losses of e^- due to adiabatic expansion and radiative losses caused by synchrotron and IC processes

Exploration of parameter space

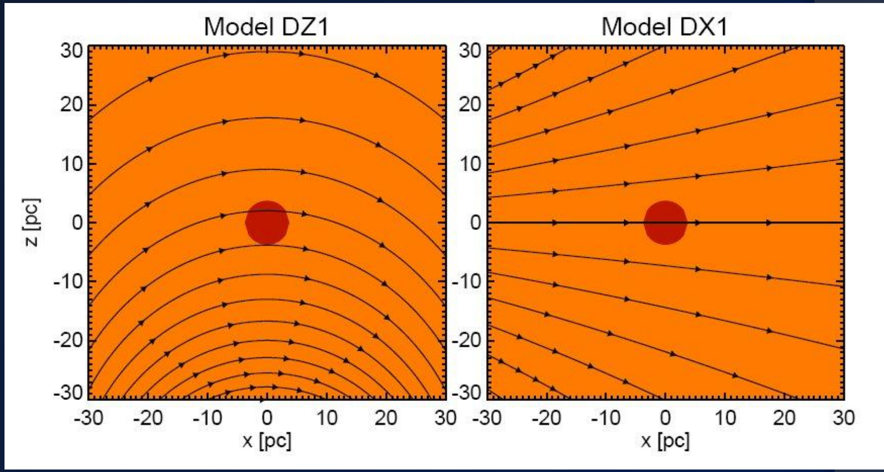
As initial conditions, we adopt parameters appropriate to reproduce SN 1006

$n_{ism} = 0.05\ cm^{-3}$; $E_{SN} = 1.4\ 10^{51}$ erg; $M_{ej} = 1.4\ M_{sun}$

v_{sh}(1000 yrs) ~ 5000 km/sec; D_{snr}(1000 yrs) ~ 17 pc

Three test cases for the MHD model

- Uniform ambient magnetic field
- Grad |B| perpendicular to the average B
- Grad |B| aligned with the average B



Three models of injection efficiency:

isotropic, q-parallel, q-perpendicular

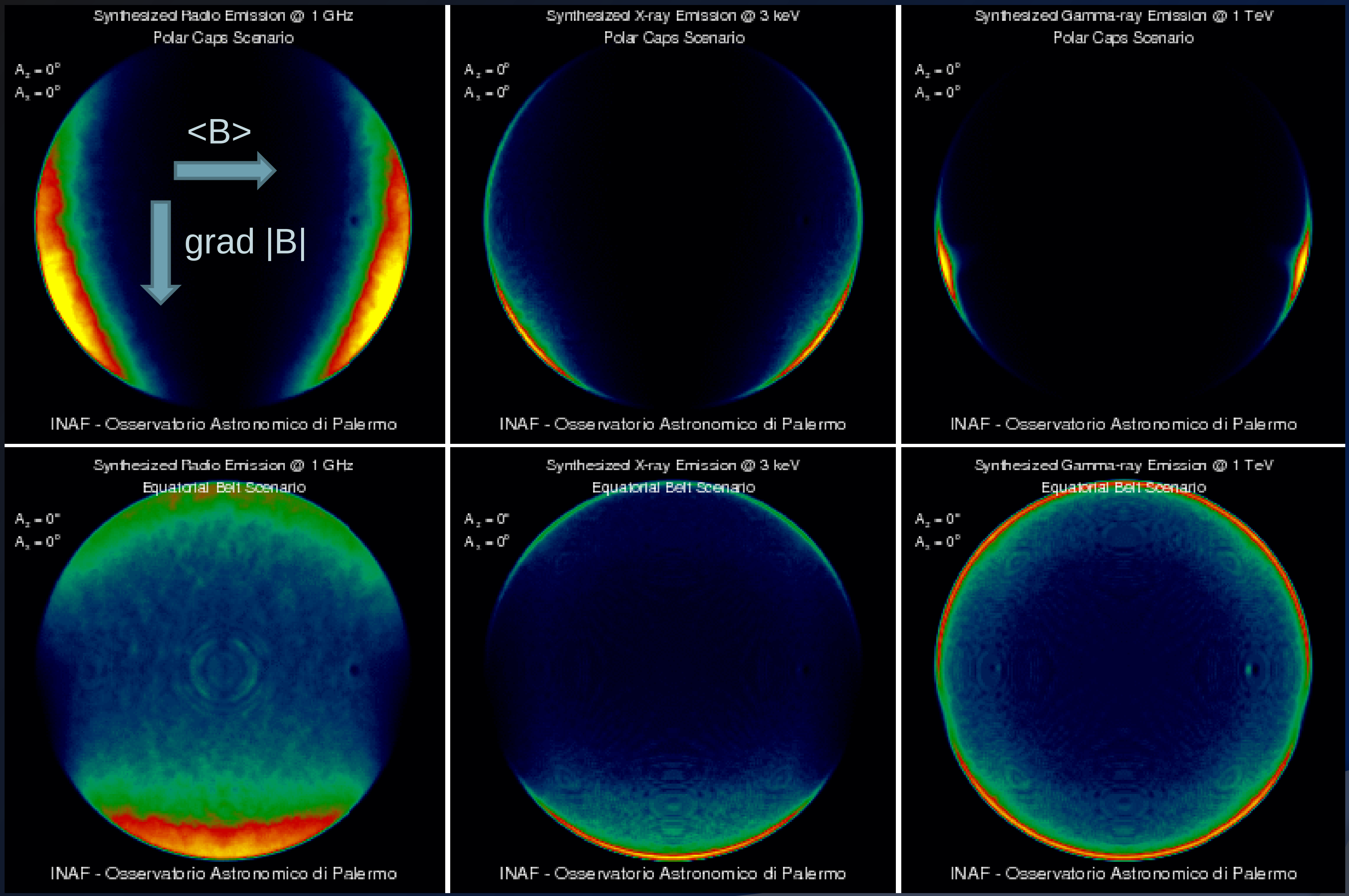
Three cases for the adiabatic index: γ = 5/3, 4/3, 1.1

Example of synthetic Images

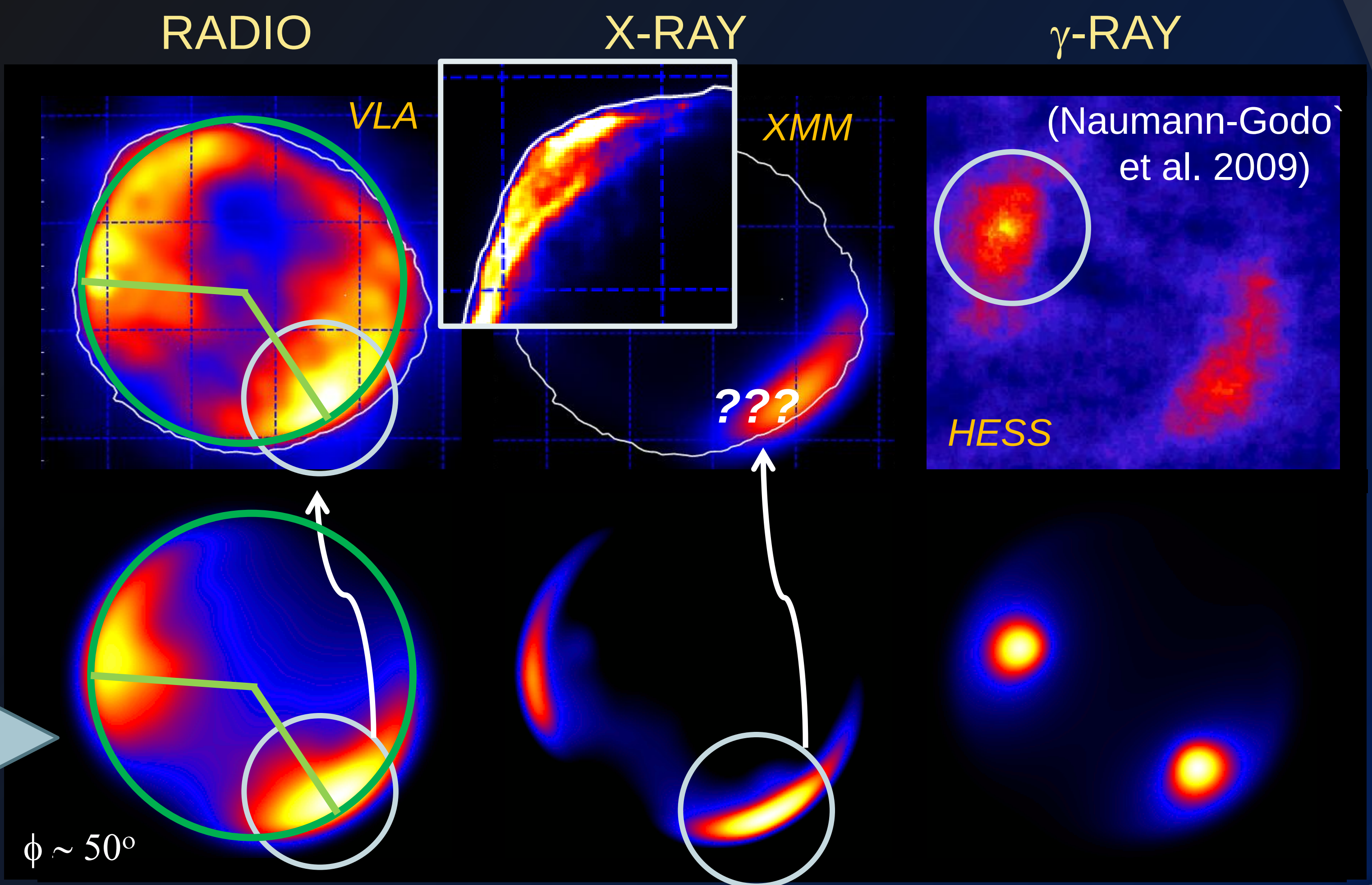
Radio | X-ray | γ-ray

Polar Caps

Equatorial Belt



The case of SN 1006



σ ~ 2 arcmin

BEST - FIT MODEL

q-parallel

See Bocchino's talk

Structure at NE important to model X-ray and γ-ray emission ?

Summary

We investigate the effects of non-uniform ISMF on brightness distribution in radio, X-rays and γ-rays

3D MHD simulations + synthesis of synch. radio, X-ray and IC γ-ray emission

- Gradient of MF strength leads to asymmetries in the morphology of BSNRs (e.g. converging arcs, limbs with different brightness) in all the bands considered (radio, X-ray and γ-ray)
- q-parallel and q-perpendicular injection models:
  limbs in the three bands nearly coincident
- q-perpendicular injection model:
  γ-ray morphology almost ring-like
- q-parallel injection model:
  recovers the observed morphology in all the bands

→ SN 1006: q-parallel injection model the most appropriate