Modeling particle acceleration and non-thermal emission in supernova remnants

S. Orlando[a], M. Miceli[b,a], S. Ustamujic[a], A. Tutone[b,c], E. Greco[b,a], O. Petruk[d], F. Bocchino[a], G. Peres[b,a]

[a] *INAF - Oss. Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy*
[b] *Dip. di Fis. e Chim., Università di Palermo, Via Archirafi 36, 90123 Palermo, Italy*
[c] *INAF - IASF, Via Ugo La Malfa 153, 90146 Palermo, Italy*
[d] *Inst. for Appl. Probl. in Mech. and Math., Naukova Street, 3-b Lviv 79060, Ukraine*

Abstract

According to the most popular model for the origin of cosmic rays (CRs), supernova remnants (SNRs) are the site where CRs are accelerated. Observations across the electromagnetic spectrum support this picture through the detection of non-thermal emission that is compatible with being synchrotron or inverse Compton radiation from high energy electrons, or pion decay due to proton-proton interactions. These observations of growing quantity and quality promise to unveil many aspects of CRs acceleration and require more and more accurate tools for their interpretation. Here, we show how multi-dimensional MHD models of SNRs, including the effects on shock dynamics due to back-reaction of accelerated CRs and the synthesis of non-thermal emission, turned out to be very useful to investigate the signatures of CRs acceleration and to put constraints on the acceleration mechanism of high energy particles. These models have been used to interpret accurately observations of SNRs in various bands (radio, X-ray and γ-ray) and to extract from them key information about CRs acceleration.

Keywords: cosmic rays, magnetohydrodynamics (MHD), radiation

Modeling SNRs...hard case

thermal and non-thermal emission in *various bands*

DSA physics

Interaction with inhomogeneities of the ISM

SN explosion mechanism?

multiple shocks

HD instabilities

Magnetic turbulence

effects of particle acceleration

multi-D

1. Introduction

- Site of CR acceleration: SNRs
- Mechanism: DSA (Diffuse Shock Acceleration)
- Energy required: 10% (to satisfy observations, i.e. non-thermal, synchrotron emission from CR electrons)
- Direct evidence of CR ions? NO (do not radiate efficiently, hints only from γ-ray analysis)

Γ-Ray production mechanisms

- Synchrotron radiation (either electrons or protons)
- Inverse Compton Scattering
- π^0 decay

$$p + p \rightarrow \pi^0 + \text{other products}$$
$$\pi^0 \rightarrow 2\gamma$$

1. Introduction

Evidence of CR ions – Impact on SNRs

- Affect the dynamics on the shock wave (and therefore on the thermal emission from the shell in different λ-bands)

- Affect the evolution on the magnetic field (signature of their presence: non-thermal emission from the electrons in different λ-bands) (e.g. Ferrand 2014)

- Separation between FS – CD in young SNRs (should be smaller than expected) (e.g. Ferrand 2010)

1. Introduction

Numerical simulations on CR acceleration at shock fronts

- PIC (Particle-in-cell) and hybrid simulations

Ions are treated kinetically and electrons as a neutralizing fluid. This allows an accurate treatment of the acceleration of the ions (i.e. cosmic rays) but not the electrons

Based on first principals and few or no parameters/approximations
High computational resources (+time), limited dynamical ranges

- 3D HD/MHD simulations

(coupled with semi-analytic models - provide a general description of the CR acceleration)

less accurate but allows to simulate the evolution of the whole remnant from the SN explosion to its interaction with the inhomogeneous and magnetized ISM.
These models include the microphysics for the evolution of SNRs (e.g. magnetic-field-oriented thermal conduction, deviations from equilibrium of ionization, radiative cooling etc) and are constrained by multi-λ observations

1. Introduction

Numerical simulations on CR acceleration at shock fronts

- PIC (Particle-in-cell) and hybrid simulations

Accurate description and a deep physical insight of the **microscopic** mechanisms for particle acceleration

- 3D MHD simulations

Description of the **macroscopic** effects of particle acceleration on the dynamics and evolution of SNRs, especially during the interaction of the remnants with the inhomogeneous ISM.

Powerful tool for observational interpretation/obtain information and constraints on the mechanisms of particle acceleration

2. Modeling the macroscopic effects of particle acceleration on the dynamics of SNRs

1st attempt: CR hydro-NEI (ChN) code (Lee et al. 2008, 2012)

- 1-D code appropriate to describe young to middle-aged SNRs
- It includes nonlinear DSA physics, and describes the CR back-pressure, the particle escape, and the magnetic turbulence generation.
- Although very sophisticated and rich in physics, cannot describe the asymmetries and the complex interaction of the SNR with the inhomogeneous ISM

2nd attempt: 3-D approach

- coupled a semi-analytical kinetic model of shock acceleration with a 3D hydrodynamic code (by means of an effective adiabatic index) (Ferrand et al. 2010)
- study the time-dependent compression of the region between the FS and RS due to the back reaction of accelerated particles.

  They found that density profiles and the thickness of the mixing region depend critically on the injection level of particles

3. Modeling the evolution from the SN to the SNR including the CRs acceleration

Need of 3D HD/MHD models

(accurately describe the structure of the ejecta and the evolution from the SN phase to the full-fledged SNR phase (e.g. Orlando 2015, 2016; Ferrand 2019; Orlando 2020)

Strategy for that:

Coupling of SN models with SNR models

- SN model: explosive nucleosynthesis, energy deposition, gravitational effects of the CCO, fallback material of the compact object

(Pre – SN structure of stellar progenitor: available stellar evolution models)

- SNR model: effects of magnetic field, radiative cooling, deviations from equil. of ionization/e^-, p^+ temperature equil., heating due to radioactive decay, back reaction of accelerated CRs, geometry+density structure of ambient medium (constrained from multi-λ obs)

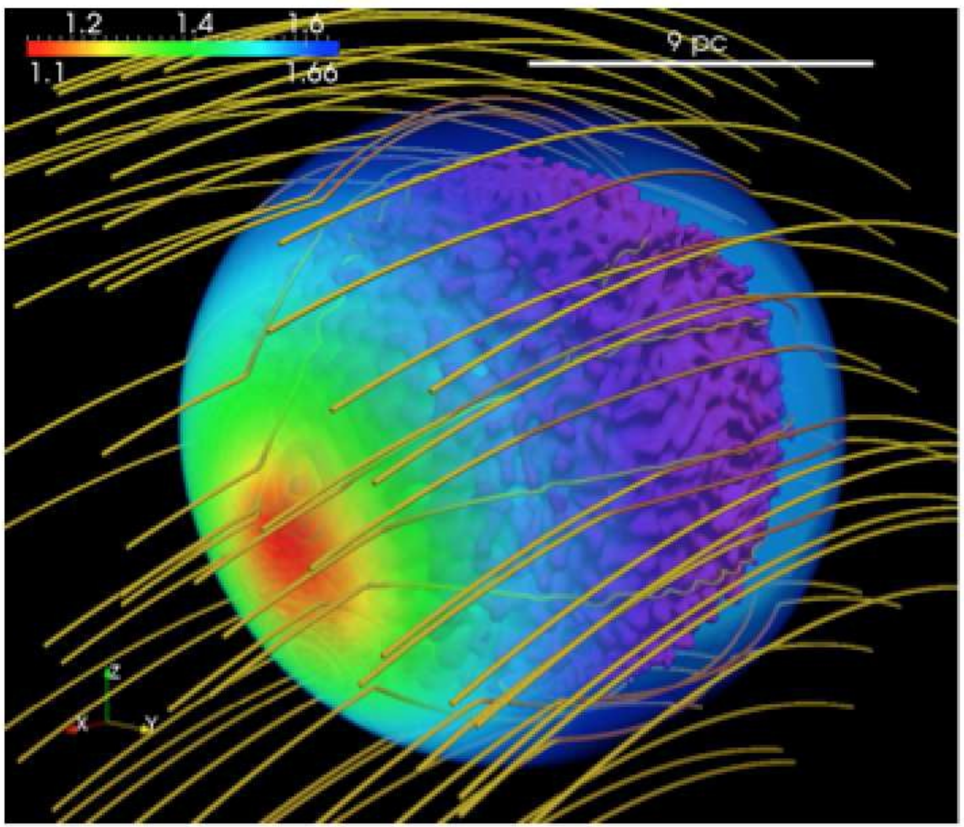
Synthesis of thermal/non-thermal emission included!!

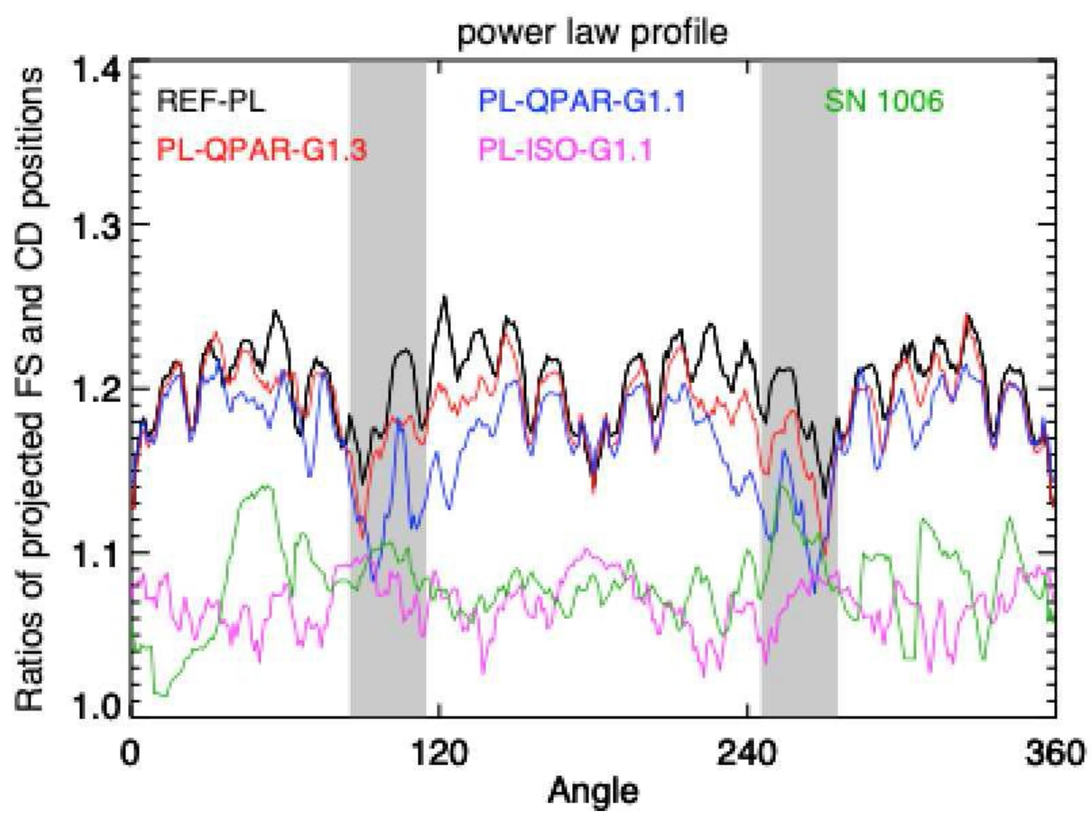
(Essential to separate the effects from CR acceleration from other effects)

3.1 Back-reaction of accelerated CRs and clumping ejecta

Mixing region in SNRs:
how much affected by accelerated CRs and how much by the intrinsic ejecta?

Models without ejecta clumping and with a dependence on the obliquity angle





Left panel: Spatial distribution of adiabatic index

Right panel: Azimuthal profile of FS/CD ratio

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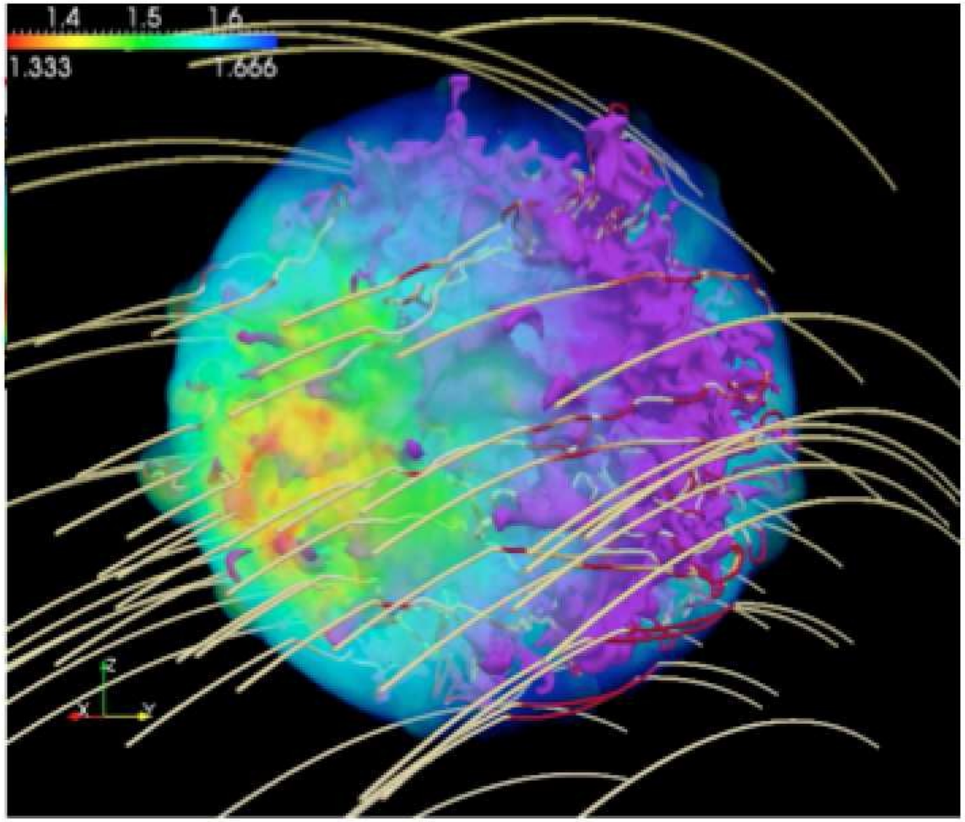

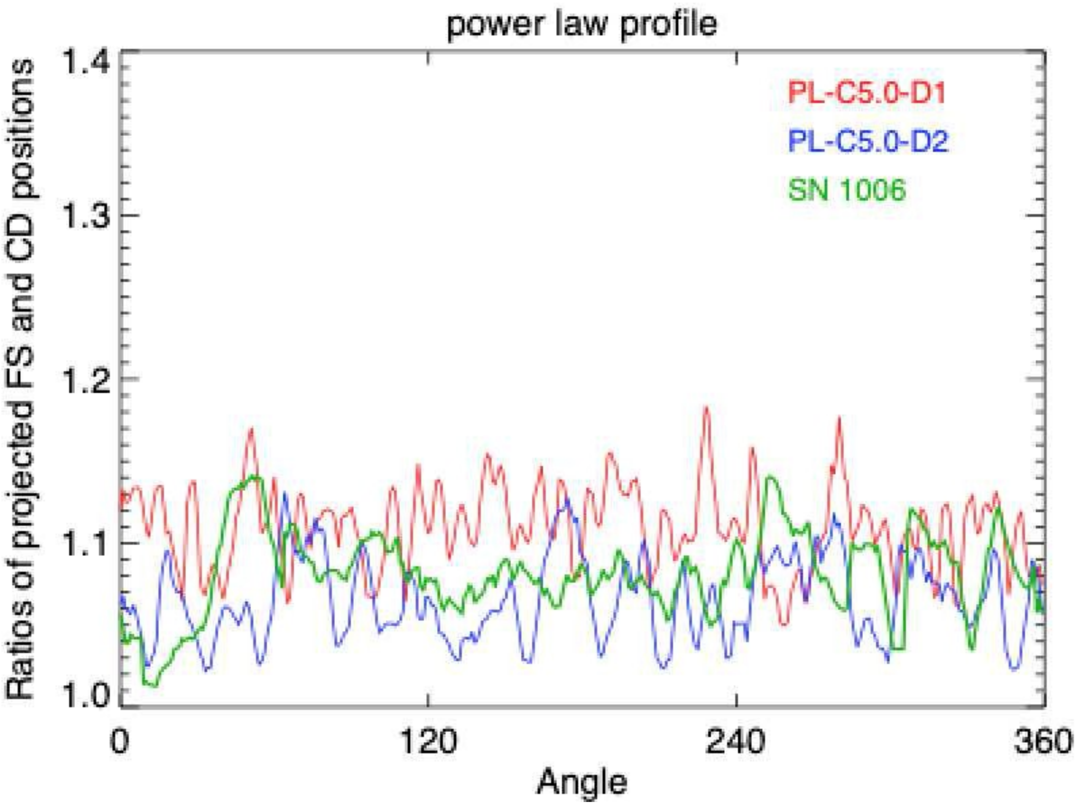

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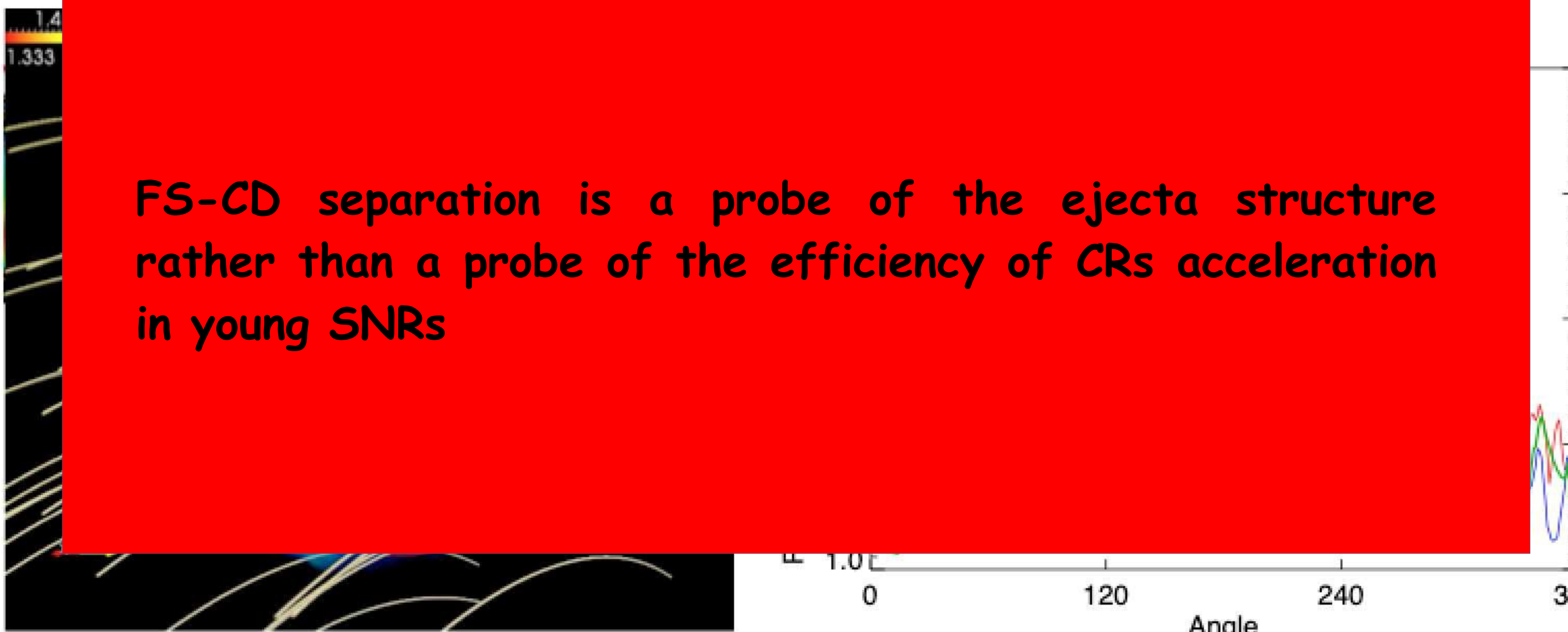


FS-CD separation is a probe of the ejecta structure rather than a probe of the efficiency of CRs acceleration in young SNRs

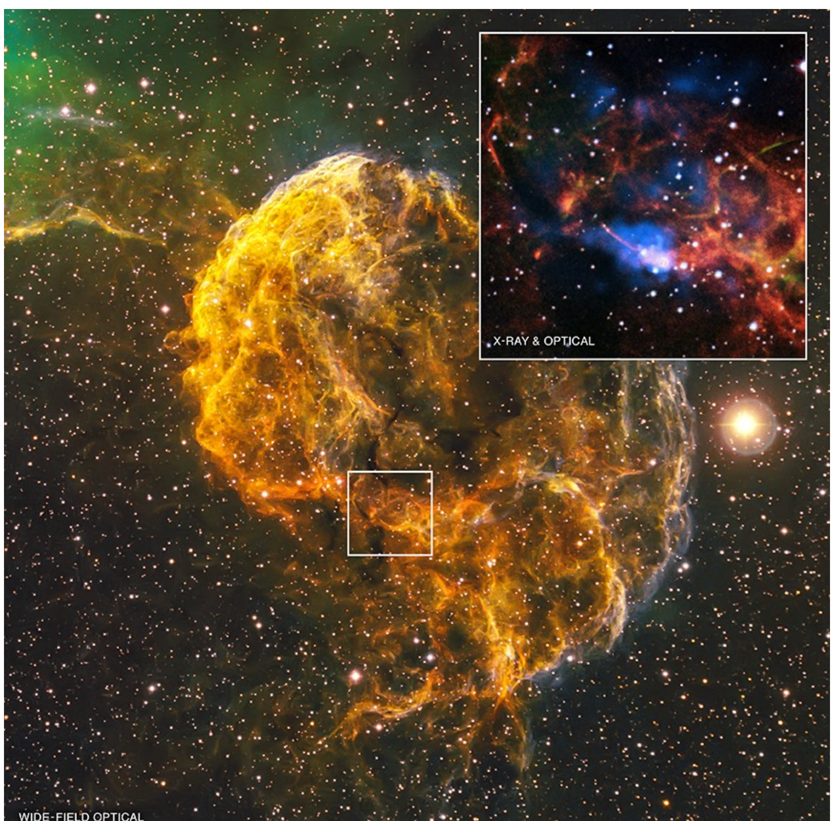
Left panel: Spatial distribution of adiabatic index

Right panel: Azimuthal profile of FS/CD ratio

3.2 Interaction of SNRs with interstellar clouds

Where γ-ray emission is dominated by protons...

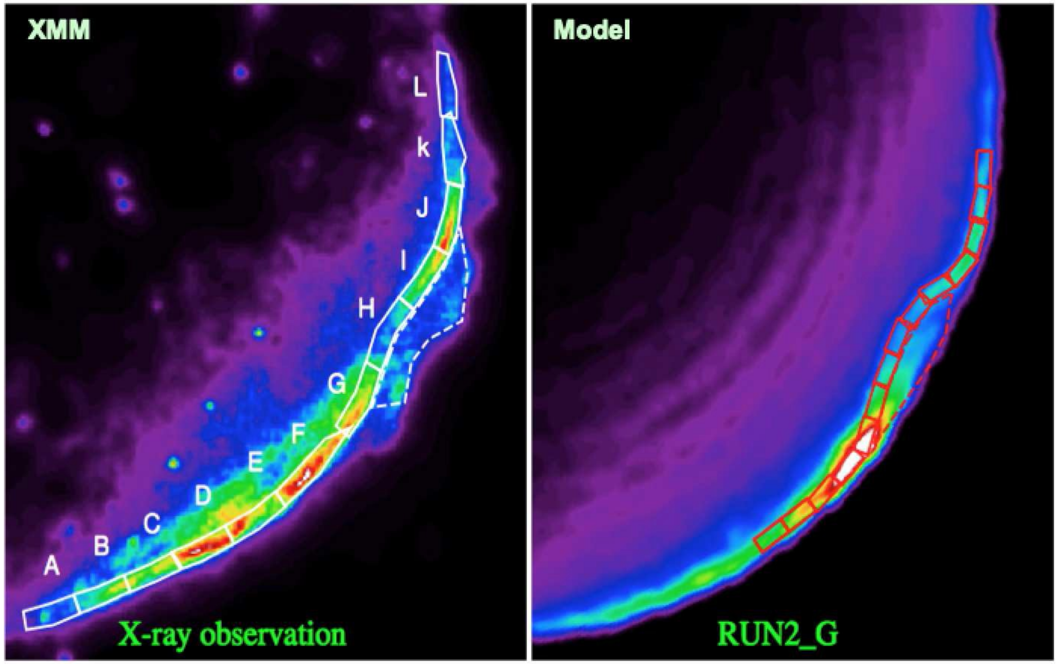
When cosmic-ray protons accelerated by SNRs penetrate into high density clouds, π0-decay gamma-ray emission is expected to be enhanced because of more frequent pp interactions relative to the ISM. Indeed, SNRs interacting with molecular clouds are the most luminous SNRs in gamma rays. The best examples of SNR-cloud interactions in our galaxy are e.g. the SNRs IC 443, SN1006, W44.

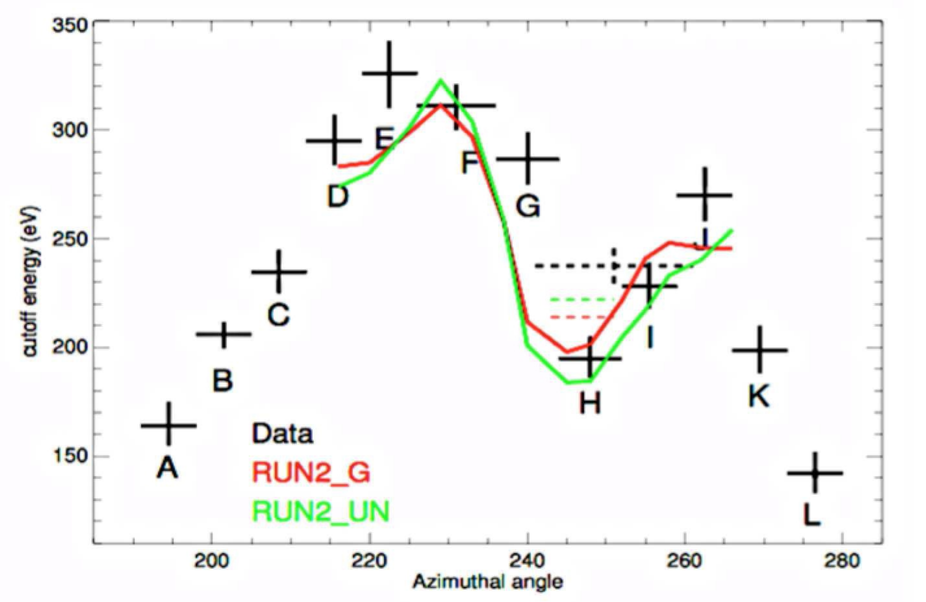


IC443 is a strong γ-ray source and one of the few remnants providing evidence for hadronic CRs acceleration

3.2 Interaction of SNR with interstellar clouds

SN1006: The shock-cloud interaction was investigated through 3D MHD simulations, including the back-reaction of particle acceleration, and describing the interaction of the remnant with the HI cloud (Miceli et al. 2016).

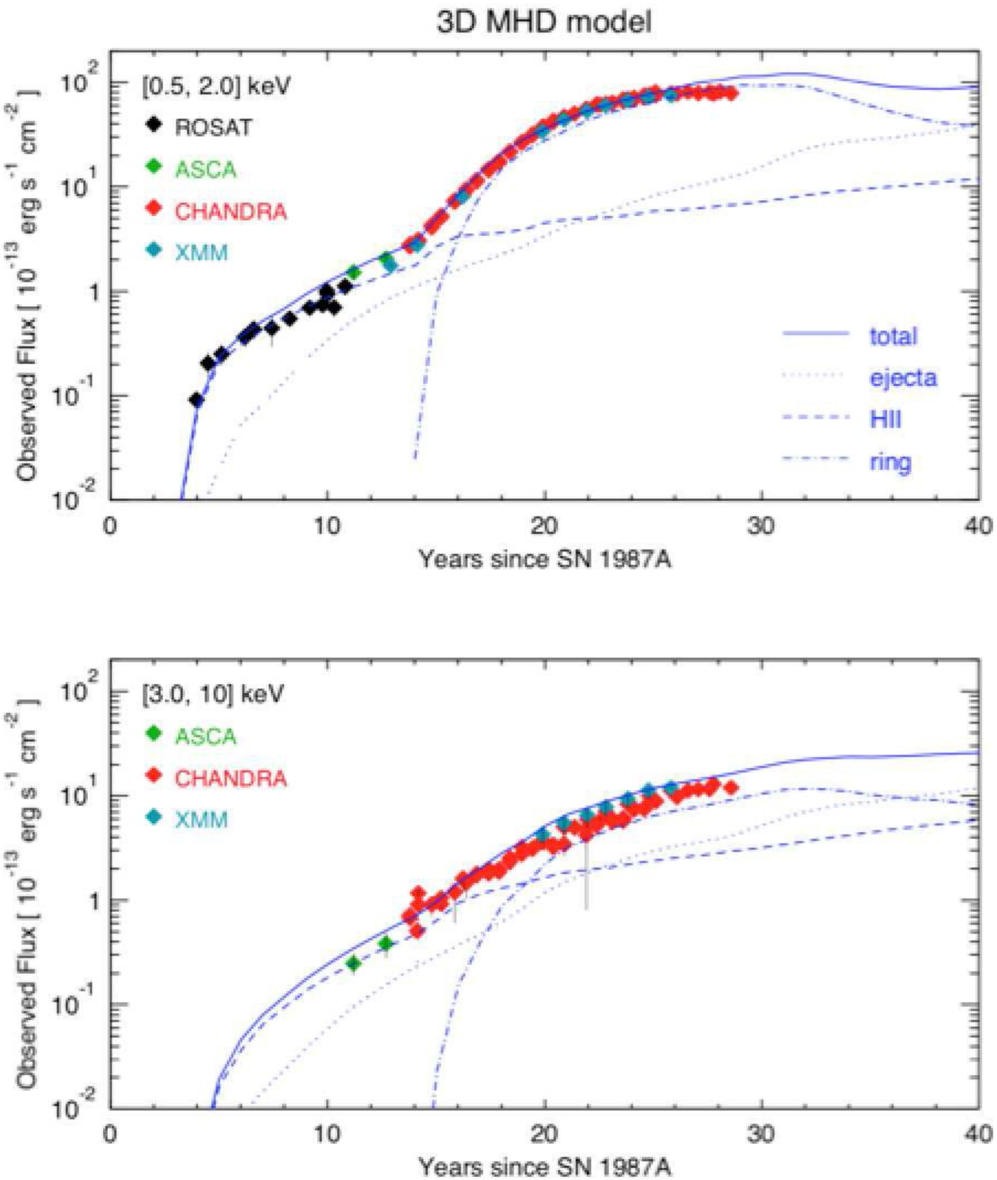


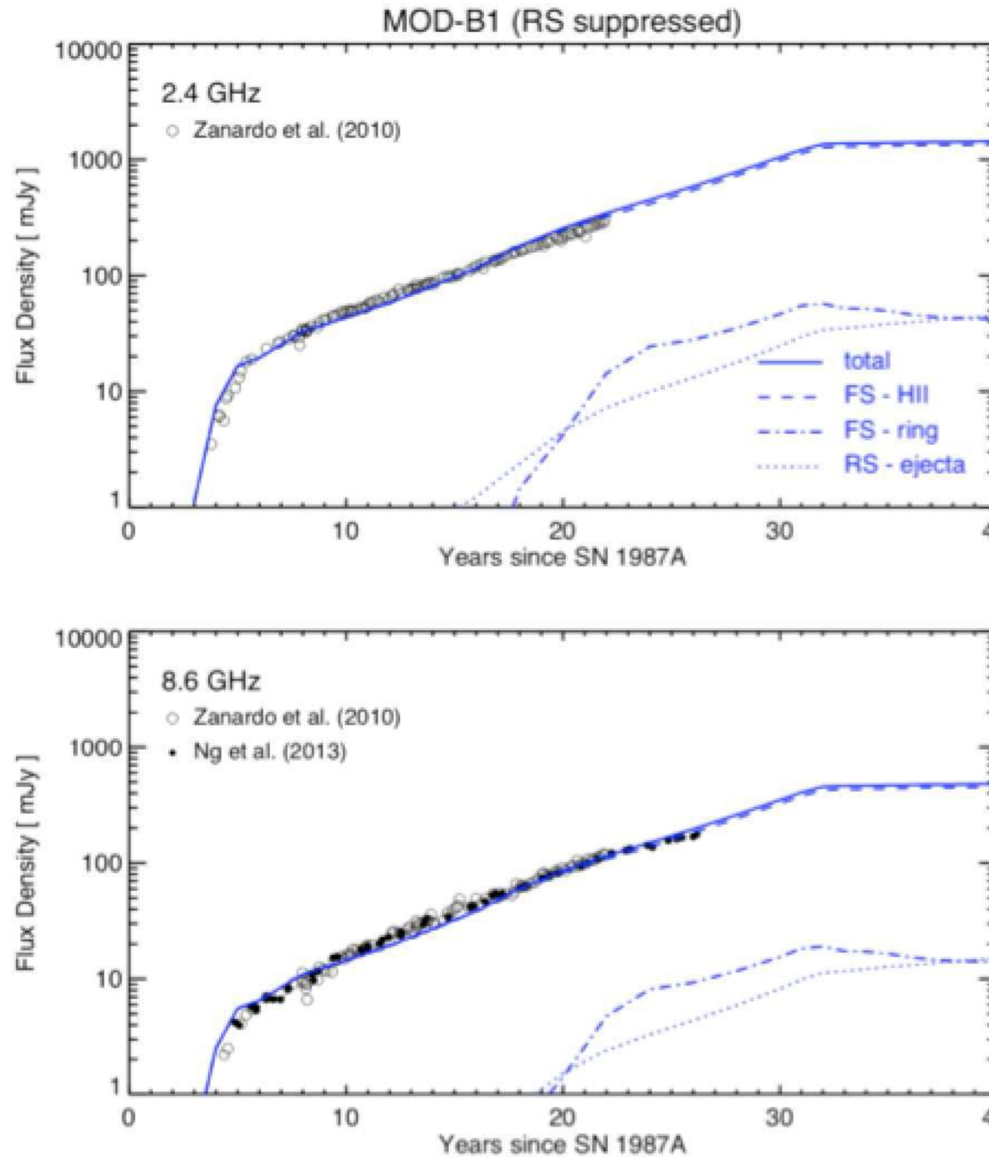


Left panel: XMM-Newton (on the left) and modeled (on the right) images of the SW limb of SN 1006 in the [2, 4. 5] keV band. The images show the regions selected for the spectral analysis of the rim. Figure adapted from Miceli et al. (2016). Right panel: the model is able to reproduce the azimuthal profile of cutoff energy inferred from observations, and in particular the drop in energy.

The synthesis of the hadronic and leptonic emission in the γ-ray band from the models and the comparison of the model results with observations collected by HESS and FERMI allowed to constrain the total hadronic energy to ~5×10^{49} erg, a value confirmed later by Condon et al. (2017).

3.3 Particle acceleration in very young SNRs: the case of 1987A





Conclusions

They discussed how models describing the evolution of SNRs can include the **macroscopic** effects of particle acceleration at SFs

These models do not describe in detail the physics of particle acceleration (as PIC/hybrid do)

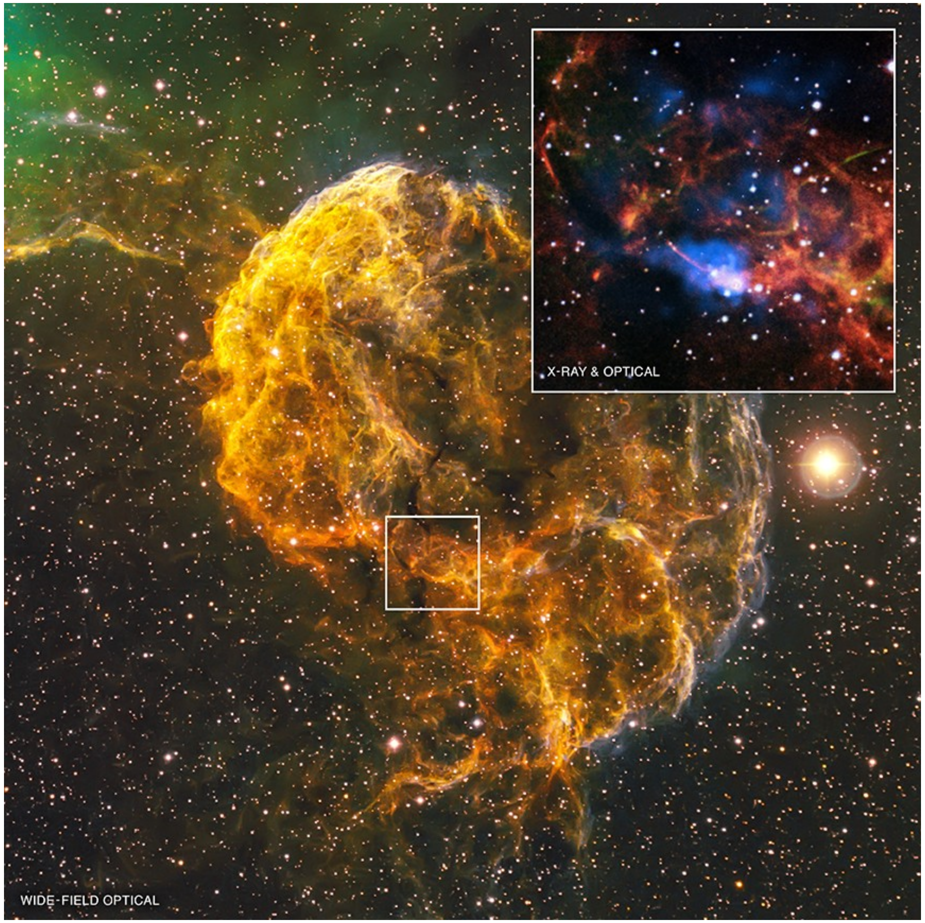
They do allow to explore large dynamical ranges, describing the evolution of SNRs (since the SN explosion) AND their interaction with inhomogeneous ISM.

Current limitations of these models include and accurate description of the back reaction of accelerated particles from first principle simulations →

Link of SNRs with their parent SN explosion and progenitor star

Crucial to know the structure of the ejecta and its anisotropies and
The structure of the ambient medium

Only then the effects of CR acceleration can be disentangled from other effects



_IC443_

Inset image: DSS + X-rays

_W44_

Blue: X-rays

Green: Infrared

Red: Molecular cloud