Constraints on cosmic-ray origin from gamma-ray observations of supernova remnants

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Accelerated particles in SNRs

Bremsstrahlung
Synchrotron emission
Inverse compton scattering
Proton-proton interaction

Electrons

Protons

Matter and photon field

Inverse Compton (+Bremsstrahlung)
Radiative processes in SNRs

=> Potential to disentangle between protons and electrons in the gamma-ray range:

- TeV-observations:
  shape of the high-energy IC component cutoff in KN-regime (ambiguous)

- GeV-observations:
  intensity & hardness of $\pi^0$ decay component

Energy Flux

$p-p$ interaction $\Rightarrow \pi^0 \Rightarrow 2\gamma$-rays

Credit: Jim Hinton
Ratios between the different radiative processes

Assume $K_{ep} = 0.01$
Photon field = CMB

Proton-proton dominates over IC for $n > 1 \text{ cm}^{-3}$

Bremsstrahlung needs $K_{ep} > 0.1$ to dominate over pp interaction


Marianne Lemoine-Goumard, IAU Symposium 2016, Crete
NASA press release (Feb 2013): CR protons in SNRs

« NASA’s Fermi Proves Supernova Remnants Produce Cosmic Rays »

Supernova W44 & IC 443 Neutral Pion Decay Spectral Fit

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The pion bump at low energy

Hadronic scenario directly produces a break at low energy
Leptonic scenario would need artificial breaks

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Going deeper with the case of IC 443

Remnant of core-collapse SN evolving in inhomogeneous environment

=> varying amount of target material

Distance of 1.5 kpc ; 0.75° diameter

Age uncertain : 3 - 30 kyr

PWN at southern edge of shell

Green : radio
Red : optical
Blue : X-rays

Lee et al. 2012
Resolving IC 443 (the Jellyfish nebula) in gamma-rays!

Fermi LAT 2010: 13 months P6V3 data → 2015: 83 months Pass 8 data
VERITAS 2007: 38hrs → 2015: 178hrs + PMT upgrade, T1 move
GeV/TeV correspondence with shock interaction gas density
Spectrally-resolved morphological analysis of IC 443

Able to resolve γ-ray emission zones on ~5 pc scales
No clear differences in spectral shape for distinct emission regions:
(e.g. dense cloud in region 1 vs. fast atomic shock in region 4)
Broken PL fits for all 4 regions: $\Gamma_1 \sim 2.3$, $\Gamma_2 \sim 2.9$, $E_b \sim 60$ GeV

$\Rightarrow$ unprecedented study of the environmental dependence of cosmic-ray diffusion in and around a hadronic accelerator

Poster S1.9 by Brian Humensky
**W49B: a young SNR in interaction with Molecular Cloud**

**SNR/MC W49B**
1 - 4 kyr
8 kpc < D < 12 kpc
Radio shell (4') + Filled with X-rays
IR, X-ray studies indicate Type Ic
~25 Msol progenitor
Detected in IR (150 GHz mapping, IRAM)
=> no spectral break (Hewitt et al., 2014)
Detected at TeV and GeV energies

**Star Forming Region W49A**
Densest part of a $10^6 M_\odot$ MC
No detection in gamma-rays
Broad-band modeling of W49B

Pion bump feature

Hadronic scenarii:
- $K_E = 0.01$
- B field of 100 - 500 $\mu$G
- Spectral shape independent of $n_H$ (if set between 100 and 1000 cm$^{-3}$)

Leptonic scenarii:
- $K_E = 1$
- B field of 20 - 100 $\mu$G

No spectral break in radio and IR => favours the hadronic scenario with dense medium

Abdalla et al., 2016, A&A submitted
Acceleration or Re-acceleration?

2 possible ways to produce the gamma-ray signal:
- Re-acceleration and compression of Galactic CRs
- Fresh acceleration and compression of particles at the shock

2 outliers: W49B & G349.7+0.2
LAT flux implies $u_{CR} \sim 10^5 \text{ eV/cm}^3$

$\Rightarrow$ re-acceleration may not be enough
$\Rightarrow$ Freshly accelerated CRs?

More details on re-acceleration in M. Cardillo’s presentation

Uchiyama et al. 2011
Both SNR and surrounding MC emit gamma-rays
After leaving the SNR, CRs diffuse along the external B-field direction
► bipolar morphology

Credit: S. Gabici

(c) M. Malkov (2012)

CR self-confinement (Exciting Alfven waves)
Escaping cosmic-rays: the case of W44

Presence of large-scale GeV emission found in the vicinity of W44


Subtraction of W44 assuming radio map = gamma-ray map

- Excess gamma-ray emission coincident with surrounding dense clouds
- Cosmic-rays that escaped from the SNR?

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Amount of escaping cosmic-rays

Energetics in broad agreement with the conjecture that SNRs are the main sources of Galactic CRs.

Solving the diffusion equation, we estimate the total kinetic energy channeled in CRs to \((0.3-3) \times 10^{50}\) erg. => SNRs are the main CR sources.

Molecular clouds illuminated by escaping CRs (assumed to be uniform within \(r<L\))
- \(L \sim 100\) pc, Mass = \(0.5 \times 10^5\) M\(_\odot\)

Diffusion coefficient of the ISM (isotropic)
- \(D(p) = D_{28} (cp/10\text{ GeV})^{0.6} 10^{28}\text{ cm}^2/\text{s}\)
SNRs detections with Fermi

Updated from Thompson, Baldini, Uchiyama (2012)
Puppis A: a transition case

- A well-defined SNR...
  - Distance of 2.2 ± 0.3 kpc
  - Physical diameter of 30 pc (0.8°)
  - Age: 3700 ± 400 yr
  - Sedov-Taylor phase
  - CCO identified as PSR J0821-4300 (X-ray pulsar, Gotthelf & Halpern, 2009)

... in a well-known environment:
- Evolving into the ISM in the vicinity of a mol. cloud
- Non radiative shocks (except at certain knots where small clumps are shocked)
- X-ray/IR correlation indicates $n \sim 4 \text{ cm}^{-3}$
Non-thermal modeling of Puppis A

- All mechanisms are viable requiring $W_{CR} \sim (1-5) \times 10^{49}$ erg but pion-decay is most reasonable:
  - IC dominates for $n < 0.3 \, \text{cm}^{-3}$
  - Brems dominates over pion-decay for $e/p > 0.1$
- One-zone models have a great difficulty explaining radio break if confirmed (would need very high B field)
- All models need a low energy max to account for the non-detection by HESS


<table>
<thead>
<tr>
<th>Model</th>
<th>Index</th>
<th>$E_{max}$ [TeV]</th>
<th>$n_H$ [cm$^{-3}$]</th>
<th>$B_{tot}$ [$\mu G$]</th>
<th>$\eta_e/\eta_p$</th>
<th>$W_p$ [erg]</th>
<th>$W_e$ [erg]</th>
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<tr>
<td>IC</td>
<td>2.1</td>
<td>0.5</td>
<td><strong>0.3</strong></td>
<td>8</td>
<td>1</td>
<td>$8.0 \times 10^{48}$</td>
<td>$2.9 \times 10^{49}$</td>
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<tr>
<td>Brems.</td>
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<td>0.5</td>
<td>4</td>
<td>13</td>
<td>1</td>
<td>$3.5 \times 10^{48}$</td>
<td>$1.3 \times 10^{49}$</td>
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<tr>
<td>$\pi^0$-decay</td>
<td>2.1</td>
<td>0.8</td>
<td>4</td>
<td>35</td>
<td>0.02</td>
<td>$4.0 \times 10^{48}$</td>
<td>$2.8 \times 10^{48}$</td>
</tr>
</tbody>
</table>
Location: the most important ingredient at gamma-ray energies

What determines the fraction of particles that become CRs?

3 golden rules of Real Estate:
LOCATION, LOCATION, LOCATION!
Young shell-type SNRs

5 shell-type SNRs detected by HESS; top 3 detected by Fermi

Poster S1.21 by Iurii Sushch on Vela Junior
The case of RCW 86

Remnant of a Type Ia SN
Associated to the historical SN 185
Age $\sim 1850$ years
Distance $\sim 2.5$ kpc

Detected at TeV and GeV energies as an extended source

Correlation between both energy range is not perfect

Very good spectral consistency

Constraints on CR efficiency within RCW 86

One-zone model (obviously too simple!):
Low density & soft particle spectrum

Two-zone model:
Relax constraints on density & particle spectrum

But, whatever the origin of the signal:
\( \eta_p \sim 2\% E_{SN} \)
\( E_{\text{max}} \sim 70 \text{ TeV} \)

Very far from an efficient accelerator!
Young shell-type SNRs in leptonic-dominated model

Using parameters from literature
• Caveat: Distance uncertainties can be large

=> Similar γ-ray luminosity for different SN type
=> Similar physical scenario?

Leptonic dominated scenario?  
Similar seed photons for IC

• Except SN 1006. Why?
  - high latitude
  - Bipolar morphology, lower Vaccel

But protons might play an important role

Acero et al., 2015, A&A
Protons leaking from RX J1713.7-3946?

TeV shell extended beyond X-ray shell in the Western part (region 3):

- detection of particle escape? (protons)
- B-field evolution explaining faster X-ray emission drop? (electrons)

Poster S1.24 by X. Zhang

P. Eger et al., ICRC 2015

Marianne Lemoine-Goumard, IAU Symposium 2016, Crete
Protons escaping HESS J1731-347?

Similar case as RX J1713.7-3946: Pure non-thermal X-ray spectrum from XMM-Newton (H.E.S.S. coll. 2011), Suzaku (Bamba, 2012)

But adjacent TeV source (HESS J1729-345) may permit to better trace CR proton escape?

Energetically plausible SNR evolution / CR escape scenario possible that explains J1729-345 through CRs illuminating a cloud

Important note: in contrast to W28, diffusion coefficient does not need to be suppressed

More details in Cui et al. 2016, A&A

Poster S1.17 by G. Puehlhofer
The Historical SNRs Cas A & Tycho

★ Tycho’s SNR
- SN 1572
- SN type: Ia
- distance: ~3 kpc
- radius: ~3.7 pc

★ Cassiopeia A
- SN ~1680
- SN type: IIb
- distance: ~3.4 kpc
- radius: ~2.5 pc

Most parameters are reasonably well known. → largely help us interpret gamma-ray results.
The young SNR Cas A

Detected at GeV & TeV energies
Pion bump feature at low energy =>
Leptonic scenario is ruled out
\[ W_{\text{CR}} = 4 \times 10^{49} \text{ erg (n = 10 cm}^{-3}) \]
\[ E_{\text{max}} = 10 \text{ TeV} \]
\[ B > 0.1 \text{ mG} \]

New Fermi data confirm the pion bump feature
=> Bremsstrahlung ruled out
But low CR efficiency and low E_{\text{max}} !

Plasma density overestimated ?
\[ W_{\text{CR}} = 2 \times 10^{50} \text{ erg (see Zirakashvili et al., 2013)} \]
The young SNR Tycho

First Hadronic scenario suggested:
Steep spectrum ($\Gamma = 2.3$)
Maximal energy > 500 TeV
B field > 200 $\mu$G
Energy content in CR ~ 6% $E_{SN}$

Lower Energy threshold for Fermi + modification of spectrum by VERITAS

Leptonic scenario is not completely ruled out
Some first thoughts

Finally: proof of proton acceleration in SNRs

Clear in SNRs interacting with MCs
Plausible in young non-thermal SNRs
Clear in the historical SN Cas A

....but :
1- The acceleration efficiency in young SNRs is generally much lower than the 10% used to maintain the CR flux in our Galaxy

2- We're far from smoking gun for PeV Galactic CRs
Very rare PeVatrons?

If 3SN/century and SNRs are PeVatrons for 10 - 100 yrs

...However, if SNRs accelerate up to PeV energies, they should still be surrounded by an over density of escaped PeV cosmic-rays (eg. Gabici & Aharonian, ApJ, 2007):

\[ t_{\text{diff}, \text{PeV}} \sim 5000 \left( \frac{d}{100 \text{ pc}} \right)^2 \left( \frac{D_{\text{PeV}}}{10^{29} \text{ cm}^2/\text{s}} \right)^{-1} \text{ years} \]

The emission from the clouds is weaker than the one from the SNR but lasts longer => enhanced probability of detection!

Need better angular resolution (correlation with gas) & increased sensitivity => CTA is well suited

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Still so much to learn! An exciting field

Future GeV/TeV studies will constrain the fraction of SN energy injected into protons/electrons & look for indirect detections of PeVatrons (with MCs)

Future > 10 TeV studies will look for PeVatrons

Future MeV-GeV studies will look for proton accelerators

A big thank to the organizers and to my collaborators in Fermi, HESS and @Bordeaux