Acceleration of cosmic rays and gamma–ray emission from supernova remnants in the Galaxy

P. Cristofari


S. Gabici, R. Terrier, S. Casanova, E. Parizot
The local cosmic ray spectrum

S. Swordy (1990)
The local cosmic ray spectrum

Bulk of CRs energy density: 1 eV cm\(^{-3}\)

Slope: \(E^{-2.7}\)

«knee»

\(~ 4\ \text{PeV}\)

S. Swordy (1990)
The local cosmic ray spectrum

Bulk of CRs energy density: 1 eV cm⁻³

1. Which sources can provide that?

Slope: E⁻².⁷

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~ 4 PeV

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1. Which sources can provide that?

2. Which acceleration mechanism?

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3. Can the sources be PeVatrons?

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(Baade & Zwicky 1934) Supernovae can provide the required energy if the acceleration efficiency ~10%

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   (Bell et al. 1978) Diffusive shock acceleration can provide an injection spectrum roughly $E^{-2}$

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B field amplification -> DSA can do it

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« knee»

$\sim 4$ PeV

S. Swordy (1990)
SNRs seen in TeV gamma rays

Tycho – VERITAS
acciari et al. (2011)

W 28 - HESS
Aharonian et al. (2006)

RXJ 1713 - HESS
Aharonian et al. (2006)

Hadronic interactions:
Pion decay

\[ p + p \rightarrow p + p + \pi^0 \]
\[ \pi^0 \rightarrow \gamma + \gamma \]
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\[ \epsilon_i \]
\[ \epsilon_f \]
Several HESS sources (extended survey) were identified as SNRs:

- RXJ 1713
- J1731
- RCW86
- W41
- W49B
- ...

+ about several unidentified sources

Population study of SNRs that one should expect to detect in the HESS survey of the galactic plane.
How many SNRs should we see at TeV energy?

What we need:

- Time and Spatial distribution of SNRs
How many SNRs should we see at TeV energy?

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Gamma emission of one SNR

Number of detectable SNRs for a given telescope
SNR distribution

What we need:

- **Time and Spatial distribution of SNRs**
  - **Time distribution:** SN rate: 3/century
  - **Spatial distribution:**

Lorimer et al. (2004)

Faucher-giguère, Kaspi (2006)
SNR distribution

What we need:

Time and Spatial distribution of SNRs

<table>
<thead>
<tr>
<th>Type</th>
<th>$\varepsilon_{51}$</th>
<th>$M_{ej,\odot}$</th>
<th>$\dot{M}_{-5}$</th>
<th>$u_{w,6}$</th>
<th>Rel. rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>1</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
<td>0.32</td>
</tr>
<tr>
<td>IIP</td>
<td>1</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>0.44</td>
</tr>
<tr>
<td>Ib/c</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0.22</td>
</tr>
<tr>
<td>IIb</td>
<td>3</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 1. Supernova parameters adopted in the simulation: supernova type (column 1), explosion energy in units of $10^{51}$ erg (column 2), mass of ejecta in solar masses (column 3), the wind mass loss rate in $M_\odot$/yr (column 4), the wind speed in units of 10 km/s (column 5), and the relative explosion rate (column 6). Values from Ptuskin et al. (2010).

Evolution of SNRs --> Chevalier 1982 Truelove & Mckee (1999)
Gas distribution

What we need:

- Time and Spatial distribution of SNRs
- Gas density distribution in the galaxy
Gas distribution

What we need:

Gas density distribution in the galaxy

Nakanishi & Sofue (2003)

HI

Nakanishi & Sofue (2006)

H₂
Gas distribution

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Particle acceleration

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We follow the approach by Ptuskin & Zirakashvili (2005)

1. Efficiency:

\[ P_{CR}^0 = \xi_{CR} \rho_{up} u_{sh}^2 \]

A fraction of the ram pressure is converted into CRs

acceleration efficiency at the shock
Particle acceleration

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Supported by theoretical work by Ptuskin, Zirakashvili, Caprioli..
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2. Spectrum:

\[ N_{CR} \propto p^{-\alpha} \]

where \( \alpha = 4...4.4 \)

Blasi (2011)
Particle acceleration – maximum energy

What we need:

- Time and Spatial distribution of SNRs
- Gas density distribution in the galaxy
- Model for acceleration of cosmic rays in one SNR

3. Maximum energy:

\[
\frac{D(E_{\text{max}})}{u_{\text{sh}}} \approx 0.05 \ldots 0.1 \, R_{\text{sh}}
\]

Ptuskin & Zirakashvili 2008
Particle acceleration – maximum energy

What we need:

Time and Spatial distribution of SNRs + Gas density distribution in the galaxy + Model for acceleration of cosmic rays in one SNR

3. Maximum energy:

\[ \frac{D(E_{\text{max}})}{u_{\text{sh}}} \approx 0.05...0.1 \, R_{\text{sh}} \]

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Volk et al. 2005
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Ptuskin & Zirakashvili 2008

X-ray filament measurements

~3.5% of shock kinetic energy into magnetic field

Volk et al. 2005

\[\frac{(B^2 + 2)}{(\gamma^2)} \times 10^2 \]

\[V_{\text{sh}}/(10^3 \text{ km/s})\]
Particle acceleration – maximum energy

What we need:

- Time and Spatial distribution of SNRs
- Gas density distribution in the galaxy
- Model for acceleration of cosmic rays in one SNR

3. Maximum energy:

$$B_{\text{down}} = B_0 \sigma \sqrt{\frac{u_{\text{sh}}^2}{v_d^2}} + 1$$

$$\frac{D(E_{\text{max}})}{u_{\text{sh}}} \approx 0.05 \ldots 0.1 R_{\text{sh}}$$

$$E_{\text{max}} \approx 280 \epsilon_5^{3/5} n_0^{-1/10} t_k^{-4/5} \text{TeV}$$

Type Ia, sedov phase

~3.5% of shock kinetic energy into magnetic field

Ptuskin & Zirakashvili 2008

Volk et al. 2005

X-ray filament measurements

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~3.5% of shock kinetic energy into magnetic field
How many SNRs should we see at TeV energy?

What we need:

3. Maximum energy (protons):

**OTHER SCENARIOS**

No field amplification

\[ B_{\text{down}} \approx \sigma B_0 \quad \Rightarrow \quad E_{\text{max}} \approx 34 \left( \frac{\varepsilon_{51}}{n_0} \right)^{2/5} t_{\text{kyr}}^{-1/5} \text{ TeV} \]

Model for acceleration of cosmic rays in one SNR

well blow the knee
How many SNRs should we see at TeV energy?

What we need:

3. Maximum energy (protons):

$B_{\text{down}} \approx \sigma B_0 \quad \Rightarrow \quad E_{\text{max}} \approx 34 \left( \frac{E_{51}}{n_0} \right)^{2/5} t_{\text{kyr}}^{-1/5} \text{TeV}$

Model for acceleration of cosmic rays in one SNR

OTHER SCENARIOS

No field amplification

Two zone model  
Atoyan, Dermer (2010)

Amplified field here

Enhanced Inverse Compton Scattering

Weak field here (damping?)
How many SNRs should we see at TeV energy?

What we need:

**ELECTRONS**

\[ K_{ep} = 10^{-5} \ldots 10^{-2} \]

Following Longair (1990)

\[ t_{\text{synch}} = t_{\text{age}} \]

\[ E_{\text{break}} \]

\[ E_{\text{max}} \approx 7.3 \left( \frac{u_{\text{sh}}}{1000 \text{km/s}} \right) \left( \frac{B_{\text{down}}}{100 \mu\text{G}} \right)^{-1/2} \]

Vannoni et al. 2009

Model for acceleration of cosmic rays in one SNR
Does this work?

RXJ 1713

Type II
age = 1630 yr
slope 4.3
d = 1 kpc
B₂ = 5 μG
Kₑₚ = 10⁻²
ξ = 0.4

Tycho

Type Ia
age = 441 yr
slope 4.25
d = 3.5 kpc
B₂ = 5 μG
Kₑₚ = 10⁻⁴
ξ = 0.18
n₀ = 0.24 cm⁻³
Log N – Log S of SNRs

1. No B field amplification

![Graph showing the relationship between number of SNRs and flux above 1 TeV.]

Number of SNRs

$F(>1 \text{ TeV}) \ [\text{cm}^{-2}\text{s}^{-1}]$

$\alpha = 4.4$

Cristofari et al. (2013)
Log N – Log S of SNRs

1. No B field amplification

~same # of hadronic and leptonic

F(>1 TeV) [cm\(^{-2}\)s\(^{-1}\)]

Number of SNRs

\(\alpha = 4.4\)

No field amplification

1% Crab

Cristofari et al. (2013)
Log N – Log S of SNRs

2. B-field amplification

Cristofari et al. (2013)
Log N – Log S of SNRs

2. B-field amplification

about the same -> all hadronic

Cristofari et al. (2013)
Log N – Log S of SNRs

3. Two-zone model

Amplified B ; $\text{Kep}=10^{-2}$
Two zones model ; $B_2=30\mu\text{G}$

Cristofari et al. (2013)
Log N – Log S of SNRs

3. Two-zone model

Amplified B ; Kep=10^{-2}
Two zones model ; B_2=30 \mu G
1% Crab

Log N – Log S of SNRs

Number of SNRs

F(>1 TeV) [cm^{-2}s^{-1}]

Cristofari et al. (2013)
Comparison with the HESS scan

- $-3^\circ < b < 3^\circ$
- $-40^\circ < l < 40^\circ$
- $-1.5 \%$ CRAB
- sensitivity scales as source extension
- PSF: $0.1^\circ$
- RXJ 1713
- HESS 1731-347
- CTB 37B
+ SNRs/MC (CTB 37A, W28...) / 17 unidentified sources

Gast et al. 2011

Figure 2: Sensitivity of H.E.S.S. to point-like $\gamma$-ray sources with an assumed spectral index of 2.5, for a detection level of 5$\sigma$ pre-trial, at $b = -0.3^\circ$, the approximate average latitude of Galactic sources. The sensitivity is expressed in units of the Crab integral flux $F(\geq 1\text{TeV}) = 2.26 \cdot 10^{-7}\text{m}^{-2}\text{s}^{-1}$. 

41
Comparison with the HESS scan

Cristofari et al. (2013)
Comparison with the HESS scan

Cristofari et al. (2013)

Too many!

3 shells+ all undid. sources

3 shells only

Number of detections

Distance [kpc]

Age [kyear]

Size [degree]

Median, resolved SNRs

Median, all SNRs

Maximum, all SNRs

Fraction

K_{ep}=10^{-2}

K_{ep}=10^{-5}
Comparison with the HESS scan

- Too many!
- Resolved SNRs are closer than point-like sources
- Horizon smaller for weaker sources

Cristofari et al. (2013)
Too many!

Resolved SNRs are closer than point-like sources

Young sources detected first

Trend in the oldest sources

Horizon smaller for weaker sources

3 shells only

3 shells+ all undid. sources

Cristofari et al. (2013)
Comparison with the HESS scan

Too many!

Resolved SNRs are closer than point-like sources

Young sources detected first

3 shells+ all undid. sources

Horizon smaller for weaker sources

Trend in the oldest sources

About 50%-50% extended and point-like sources

Cristofari et al. (2013)
Comparison with the HESS scan

Substantial agreement between data and expectations
(no complete catalogue of SNR available at TeV energies)

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- $L_{CR}^{MW}$ up by a factor of $f$: each SNR factor of $f$ brighter
  --> visible up to a distance $f_{1/2}$ further
  --> visible within volume $f$ larger  -->  $f$ more sources!