SUPERNOVA REMNANTS IN THE VERY-HIGH-ENERGY SKY: PROSPECTS FOR CTA

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SNRs in the TeV sky

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Gamma rays from SNRs

Hadronic interactions:

- **Pion decay**

Leptonic interactions:

- **Inverse Compton scattering**

**Situation unclear for many SNRs:** instead of individual study, study of the entire population

Aharonian et al. (2006)

Aharonian et al. (2009)

Acciari et al. (2011)

RXJ 1713 - HESS

RCW 86 - HESS

Tycho – VERITAS
Cherenkov Telescope Array (CTA)

H.E.S.S.

\[ F(>1 \text{ TeV}) \]

\[ \approx 15 \text{ mCrab} \]
\[ \approx 0.1^\circ \]
\[ |l|<40^\circ ; |b|<3^\circ \]

CTA

\[ \approx 1 \text{ mCrab} \]
\[ \approx 0.05^\circ \]
\[ |l|<60^\circ ; |b|<2^\circ \]

\[ \approx 3 \text{ mCrab} \]
\[ \approx 0.05^\circ \]

All-sky survey
A Monte Carlo approach

What we need:

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

Gamma emission of one SNR

Number of detectable SNRs by a given telescope
Time and spatial distribution of SNRs

Time distribution: SN rate: 3/century

Spatial distribution:

\[ \rho(R) = A R^n e^{-R/\sigma} \]

\[ A = 64.6 \text{ kpc}^{-4.35} \]
\[ n = 2.35 \]
\[ \sigma = 1.528 \text{ kpc} \]
\[ \rho(8.5 \text{ kpc}) = 36 \text{ kpc}^{-2} \]

SN progenitor types

- Thermonuclear
- Core-collapse

<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>
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<tr>
<td>IIa</td>
<td>1</td>
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<tr>
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<td>IIb</td>
<td>3</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>0.02</td>
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</tbody>
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Faucher-giguère, Kaspi (2006)

Ptuskin et al. (2010)
Evolution of SNRs: type Ia

\[ R_{sh} = 5.3 \left( \frac{E_{51}}{n_0 M_{ej,\odot}} \right)^{1/7} t_{kyr}^{4/7} \text{ pc} \]

\[ u_{sh} = 3.0 \times 10^3 \left( \frac{E_{51}}{n_0 M_{ej,\odot}} \right)^{1/7} t_{kyr}^{-3/7} \text{ km/s} \]

\[ t \gg 260 \left( \frac{M_{ej,\odot}}{1.4} \right)^{1/5} E_{51}^{-1/2} n_0^{-1/3} \text{ yr} \]

\[ R_{sh} = 4.3 \left( \frac{E_{51}}{n_0} \right)^{1/5} t_{kyr}^{2/5} \left( 1 - \frac{0.06 M_{ej,\odot}^{5/6}}{E_{51}^{1/2} n_0^{1/3} t_{kyr}} \right)^{2/5} \text{ pc} \]

\[ u_{sh} = 1.7 \times 10^3 \left( \frac{E_{51}}{n_0} \right)^{1/5} t_{kyr}^{-3/5} \left( 1 - \frac{0.06 M_{ej,\odot}^{5/6}}{E_{51}^{1/2} n_0^{1/3} t_{kyr}} \right)^{-3/5} \text{ km/s} \]


Type II

Thin Shell approximation

Momentum conservation

\[ \frac{d}{dt} (M u_{sh}) = 4\pi R_{sh}^2 P_{in} \]

Energy conservation

\[ E = \frac{4\pi}{3(\gamma + 1)} P_{in} R_{sh}^3 + \frac{1}{2} M u^2 \]

Ostriker & Mckee (1988)
Gas distribution

We are here

We extrapolate using fits from Shibata et al. (2010)

HI

Nakanishi&Sofue (2003)

H$_2$

Nakanishi&Sofue (2006)
1. Efficiency:

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

Acceleration efficiency at the shock

\[ \xi_{CR} = \eta_{CR} \approx 0.1 \]

Supported by theoretical work Caprioli (2010), Ptuskin & Zirakashvili (2008)

2. Slope of accelerated particles: free parameter

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

\[ \alpha = 4.1...4.4 \]

3. Maximum energy of accelerated protons

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

Loss-limited X-ray filaments: fraction of kinetic energy into magnetic field

\[ B_{down} = \sigma B_0 \sqrt{(u_{sh}/v_d)^2 + 1} \]
Particle acceleration: electrons

\[ N_p \propto E^{-\alpha} \]

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

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

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

Longair (1990)

acc rate= synch loss rate

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

Vannoni et al. 2009
Number of detections by CTA

\[ \approx 400 \text{ SNRs} \]

\[ \approx 30 \text{ SNRs} \]

Above the most optimistic scenario with H.E.S.S.

Cristofari et al. 2017
α = 4.1
$K_{ep} = 10^{-2}$

≈ 500 SNRs
≈ 350 SNRs
≈ 180 SNRs

Cristofari et al. (2017)
Number of detections by CTA

F(>1 TeV)

F(>10 TeV)

Cristofari et al. 2017
Conclusions and future perspectives

• A new test for the SNR hypothesis

• Constraining parameters governing particle acceleration

• Estimation on the SNR population accessible by CTA:
  – Improvement compared to H.E.S.S
  – Characterization of the population
    • Detection ≈ 22 - 120 SNRs
    • Size ≈ 0.2°
    • Distance ≈ 7-10 kpc
    • Ages ≈ 4-6 kyr

• Results of our approach confronted with other instruments (HAWC, HiSCORE)

• Detections of neutrinos from SNRs, search of PeVatrons