Evidence of hadronic emission in middle-aged SNRs

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2 classes of gamma-rays SNRs

<table>
<thead>
<tr>
<th>Name</th>
<th>Age</th>
<th>dist</th>
<th>$E &gt; 100$ MeV</th>
<th>$1$ GHz (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CasA</td>
<td>330</td>
<td>3.4</td>
<td>$10^{37}$</td>
<td></td>
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<tr>
<td>Tycho</td>
<td>400</td>
<td>3.5</td>
<td>$10^{38}$</td>
<td></td>
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<tr>
<td>VelaJr</td>
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<td>0.2</td>
<td>$10^{35}$</td>
<td></td>
</tr>
<tr>
<td>RXJ1713</td>
<td>1000</td>
<td>1.2</td>
<td>$10^{36}$</td>
<td></td>
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<tr>
<td>W49B</td>
<td>2000</td>
<td>8.0</td>
<td>$10^{39}$</td>
<td></td>
</tr>
<tr>
<td>CTB37A</td>
<td>2000</td>
<td>10.3</td>
<td>$10^{37}$</td>
<td></td>
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<tr>
<td>gammacygni</td>
<td>15000</td>
<td>0.8</td>
<td>$10^{36}$</td>
<td></td>
</tr>
<tr>
<td>cygnusloop</td>
<td>17000</td>
<td>0.5</td>
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<td>W51C</td>
<td>20000</td>
<td>6.0</td>
<td>$10^{38}$</td>
<td></td>
</tr>
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<td>W44</td>
<td>20000</td>
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<td>$10^{37}$</td>
<td></td>
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<tr>
<td>G353.6-0.7</td>
<td>27000</td>
<td>3.2</td>
<td>$10^{36}$</td>
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<td>IC443</td>
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<td>1.5</td>
<td>$10^{35}$</td>
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<tr>
<td>W28</td>
<td>40000</td>
<td>2.0</td>
<td>$10^{37}$</td>
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</tr>
</tbody>
</table>
2 classes of gamma-rays SNRs

\[ E > 100 \text{ MeV} \]

![Plot showing luminosity vs. age for SNRs with different classes.](image-url)
2 classes of gamma-rays SNRs

- Mixed Morphology SNRs
  - Interacting with MCs
- Shell-like SNRs
SNR W44

Age: ~ 20000 yr
Distance: ~ 3 Kpc
Type: mixed-morphology

* Expanding in a dense medium
  ~100 cm$^{-3}$  [Reach et al. 2005]

Maser OH (1720 Hz) emission
from SNR-MC interaction
[Claussen et al. 1997,
Hoffman et al. 2005]

* Strong non-thermal emission in
  radio e gamma-ray band

Observed over very wide range
in radio (10 MHz to 10 GHz)
and gamma (50 Mev-50 GeV)
The radio spectrum of W44 is a power-law featureless in the frequency range $\sim 10$ MHz - 10 GHz (Castelletti et al 2007)

$$S \text{(Jy)} = \nu^{-0.37 \pm 0.02}$$

Corresponding to an electrons spectrum:

$$F \sim E^{-1.74} \quad [\text{particles / cm s MeV}]$$

$$E \sim 300 \text{ MeV} - 10 \text{ GeV} \quad (B = 10 \text{ uG})$$

$$\sim 100 \text{ MeV} - 3 \text{ GeV} \quad (B = 100 \text{ uG})$$
Fermi detection of W44

400 MeV < E < 50 GeV

Abdo et al. 2010, Science, 327

E > 2 GeV
AGILE detection of W44

50 MeV < E < 10 GeV

(Giuliani et al. 2011 ApJL)
IC, ISRF seed photons

IC, CBR seed photons
Leptonic model: Bremsstrahlung

**Ambient:**
- $B: 20 \, \mu G$
- $n: 300 \, cm^3$

**Electrons Spectrum:**

$$F_e(E) = K_e \left( \frac{E}{E_c} \right)^{p_1} \left( \frac{1}{2} \left( 1 + \frac{E}{E_c} \right) \right)^{p_1 - p_2}$$

- $p_1 = 0$
- $p_2 = 3.3$
- $E_c = 1 \, GeV$
Leptonic model: Bremsstrahlung, $B = 200$

**Ambient:**

$B: 200 \mu G$

$n: 5000 \text{ cm}^{-3}$

**Electrons Spectrum:**

$$F_e(E) = K_e \left( \frac{E}{E_c} \right)^{p_1} \left( \frac{1}{2} \left( 1 + \frac{E}{E_c} \right) \right)^{p_1 - p_2}$$

$p_1 = 0$

$p_2 = 8$

$E_c = 1 \text{ GeV}$
Hadronic model!
Protons Spectrum:
\[ F \sim E^{-p} \exp\left(-\frac{E}{E_c}\right) \]
\[ p = 3.0 \pm 0.1 \]
\[ E_c = 6 \pm 1 \text{ GeV} \]

Electrons Spectrum:
\[ F \sim E^{-p} \exp\left(-\frac{E}{E_c}\right) \]
\[ p = 1.74 \]
\[ E_c = 10 \text{ GeV} \]

Ambient:
\[ B = 70 \text{ microG} \]
\[ n = 100 \]
Gamma-rays emission in W44 is hadronic

e / p < 0.1

p. spectrum has a peak \( \sim 6 \text{ GeV} \) (and slope \( p \sim 3 \) for \( E > 6 \text{ GeV} \))

but:

Is W44 a typical SNR?

What about the curvature of the spectrum?

Spatial variation of the spectrum?
SNRs at “low” energy: diffusion of CRs (W28)
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In a diffusion regime CRs fill the volume around SNRs up to:

\[ R \sim (2D(E) t)^{0.5} \]

For middle-aged SNRs (10^4 yrs) and slow D (\( \sim 1-2 \times 10^{26} \) (E/10 GeV)^0.5):

\[ R \sim 10 \text{ pc} \]

--> low-energy cutoff in the CRs spectrum @ \( \sim 10 \) GeV

Summary

° 2 classes : young and m.a. interacting with mol. clouds

° Protons have been found in SNRs! (at least in m.a. SNRs...)

° Spectral break @ GeV

° Diffusion plays an important role

→ Need for new radio and gamma-rays data!
Backup slides
Ion-neutral collisions in the remnant surrounding lead to the steepening of the energy spectrum of accelerated particles by exactly one power.

The spectral break is caused by a partial evanescence of Alfven waves that confine particles to the accelerator.
Crushed Molecular Clouds (Uchiyama et al. 2012)

\[ n_{e,p}(p) = k_{e,p} p^{-1.74} \exp(-p/p_c) \]

\[ p_c = 10 \text{ GeV } c^{-1} \]

\[ n \approx 7 \times 10^3 \text{ cm}^{-3} \]

\[ B \approx 800 \text{ microG} \]
Leptonic models

Electrons energy distribution:

\[ F_e(E) = K_e E^{-p} e^{-\frac{E}{E_c}} \]

\[ F_e(E) = K_e E^{-p} e^{-\frac{E_c}{E}} \]

\[ F_e(E) = K_e \left(\frac{E}{E_c}\right)^{p_1} \left(\frac{1}{2} \left(1 + \frac{E}{E_c}\right)\right)^{p_1-p_2} \]

Gamma-rays emission process:

- *Inverse Compton* (B free parameter)
  - on ISRF photons
  - on CMB photons

- *Bremsstrahlung* (B, n free parameters)
Leptonic model: IC, ISRF seed photons

Ambient: \( B: 3 \mu G \)
\( n: 1 \text{ cm}^{-3} \)

Electrons Spectrum:

\[
F_e(E) = K_e \left( \frac{E}{E_c} \right)^{p_1} \left( \frac{1}{2} \left( 1 + \frac{E}{E_c} \right) \right)^{p_1-p_2}
\]

\( p_1 = 0 \)
\( p_2 = 8 \)
\( E_c = 22 \text{ GeV} \)
Leptonic model: IC, CBR seed photons

Ambient: \( B : 10 \mu G \)
\( n : 1 \text{ cm}^{-3} \)

Electrons Spectrum:

\[
F_e(E) = K_e \left( \frac{E}{E_c} \right)^{p_1} \left( \frac{1}{2} \left( 1 + \frac{E}{E_c} \right) \right)^{p_1 - p_2}
\]

\( p_1 = 0 \)
\( p_2 = 8 \)
\( E_c = 700 \text{ GeV} \)
2 classes of gamma-rays SNRs

\[ L_{\text{gamma}}(E) = \sigma(E) \cdot c \cdot N_p(E) \cdot n \]
2 classes of gamma-rays SNRs

\[ L_{\gamma}(E) = \sigma(E) c N_p(E) n \]

100 cm\(^{-3}\)

1 cm\(^{-3}\)
Curvature of the gamma-ray spectrum: Spectral break @ GeV!
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“W44-like” SNRs
radio and μwave

Tens of MeV