Latest results on SNRs and PWNe in the Milky Way as seen in VHE gamma-rays

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Chaves et al. HESS (2008)
Outline: TeV astronomy

Individual sources & multi-wavelength observations

- Shell-type SNRs
- Plerionic SNRs (« PWNe »)
  - Known PWNe
  - PWN candidates

Other sources & surveys

- Some cases in between...
- …diffuse VHE emission?

Concluding remarks and perspectives
Shell-type SNRs: RX J1713.7-3946

H.E.S.S. image
1-3 keV ASCA contours

\[ \Gamma = 2.04 \pm 0.04 \]
\[ E_c = 17.9 \pm 3.3 \text{ TeV} \]
Index constant across SNR

Nature of the TeV emission: Inverse-Compton or $\pi^0$ decay?

Particles of >100 TeV inside the SNR...

\[ d = 1.3 \pm 0.4 \text{ kpc... AD 393?} \]
No thermal X-ray emission: $n < 0.02 \text{ cm}^{-3}$
(Cassam-Chenaï et al. 2004)
Shell-type SNRs: RX J0852-4622 (aka Vela Jr)

**H.E.S.S. image**

Aharonian et al. (2007b)

**Power-law $\Gamma = 2.24 \pm 0.04$ with indication of a cutoff?**

**Nature of the TeV emission:**
Inverse-Compton or $\pi^0$ decay?

$d = 0.25 - 1$ kpc... age?
No thermal X-ray emission: $n < 0.03$ cm$^{-3}$
(Slane et al. 2001)

Particles of $\sim 100$ TeV inside the SNR...
Shell-type SNRs: RCW 86

Both shell and uniform sphere fit the data...

\[ v_s \sim 2700 \text{ km/s} \ldots \text{SN 185? } d = 1 \text{ kpc?} \]

Faint thermal X-ray emission (Vink et al. 2006)

Nature of the TeV emission:
Inverse-Compton or \( \pi^0 \) decay?

Particles of \( \sim 100 \text{ TeV} \) inside the SNR...
Shell-type SNRs: SN 1006

Naumann-Godo et al. (HESS Collaboration, 2008)

H.E.S.S. Image & Chandra (smoothed) contours

~0.5°

See the talk by M. Naumann-Godo on thursday for more details...

Nature of the TeV emission: Inverse-Compton or $\pi^0$ decay?

Particles of ~100 TeV inside the SNR...
Shell-type SNRs

Pro-hadrons:
- Amplified B-field from the thinness of X-ray filaments (& variability)

Pro-leptons:
- Lack of thermal X-ray emission
- Nature of X-ray filaments

Limitations:
- Size of filaments << VHE PSFs
- Non-imaging instruments > 10 keV

RX J1713.7-3946
(Berezhko & Völk 2008)
VHE Pulsar Wind Nebulae & candidates

Half of the H.E.S.S. sources is likely associated with a PSR

Young PWNe: Crab nebula, MSH 15-52... and G21.5-0.9, Kes 75

PSR J1833-1034

$\tau_c = 4.7$ kyr, $\dot{E}_{36} = 33$, $d \sim 5$ kpc

age < 1 kyr (Biethenholtz et al. 2008)

PSR J1848-0258 (Gotthelf 2000)

$\tau_c = 723$ yr, $\dot{E}_{36} = 8.3$

$d \sim 6$ kpc (Leahy & Tian 2008)
VHE Pulsar Wind Nebulae & candidates

Half of the H.E.S.S. sources is likely associated with a PSR

**Evolved (offset) PWNe: J1825 and Vela X** (De Jager & Djannati-Ataï 2008)

<table>
<thead>
<tr>
<th>Source</th>
<th>PSR</th>
<th>$\tau_c$ (kyr)</th>
<th>$\dot{E}_{36}$</th>
<th>Origin</th>
</tr>
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<tbody>
<tr>
<td>HESS J1825-137</td>
<td>J1826-1334</td>
<td>21.4</td>
<td>2.8</td>
<td>4kpc</td>
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<td>13 d</td>
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<tr>
<td>HESS J0835-455</td>
<td>B0833-45</td>
<td>11.3</td>
<td>6.9</td>
<td>300pc</td>
</tr>
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<tr>
<td></td>
<td></td>
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<td>1.5 d</td>
</tr>
</tbody>
</table>
VHE Pulsar Wind Nebulae & candidates

Association based on:

Presence of a nearby (and energetic) PSR

Theoretical background

- Particle acceleration in PSR/PWN (Arons 2007, Bucciantini 2008)
- Evolution of a PWN in the ISM (Blondin et al. 2001, van der Swaluw et al. 2004)

Characteristics:

Inhomogeneous ISM and/or high $v_{\text{PSR}}$

Evolved systems ($\tau_c \geq$ several kyrs)

Low B (a few $\mu$G) in the VHE emissive region (de Jager & Djannati-Ataï 2008)
VHE Pulsar Wind Nebulae & candidates

**HESS J1809-193 / PSR J1809-1917**
(Aharonian et al. 2007, Renaud et al. HESS 2008)

PSR J1809-1917: $\tau_c = 51$ kyr, $\dot{E}_{36} = 1.8$, $O \sim 7$ d, $d_{3.5\text{kpc}}$, $L_{1-10\text{TeV}}/\dot{E} \sim 0.015$ $d^2_{3.5\text{kpc}}$

VLA 1.4 GHz (Brogan et al., Helfand et al. 2006)
VHE Pulsar Wind Nebulae & candidates

**HESS J1356-645 / PSR J1357-6429**
( Renaud et al. HESS 2008, Aharonian et al. in prep)

**PSR J1357-6429:**
\[ \tau_c = 7.3 \text{ kyr}, \dot{E}_{36} = 3.1, \]
\[ O \sim 5 \, d_{2.5\text{kpc}} \text{ pc}, \]
\[ L_{1-10\text{TeV}} / \dot{E} \sim 0.002 \, d_{2.5\text{kpc}}^2 \]

But extended radio emission seen at 0.84, 2.4, 4.85 GHz... «relic» PWN?

3 SNR candidates (Duncan et al. 1997) ...
Some cases in between: HESS J1731-347

A new shell-type SNR G353.6-0.7 (Tian et al. 2008)

Non-thermal shell-type radio emission with $R \sim 0.25^\circ$
HI absorption towards adjacent HII region: $d = 3.2 \pm 0.8$ kpc $\rightarrow R \sim 14 \ d_{3.2}$ kpc pc
ROSAT emission coincident with lower half of the SNR... thermal emission? age?
Some cases in between: CTB complex

- **CTB complex**
  - MGPS 843 MHz contours
  - $d = 5-9$ kpc (Brand & Blitz 1993)
  - Age $> 1500$ yrs... AD 393? (Clark et al. 1975)
  - No maser emission
  - $\text{rms} = 2.6' \pm 0.6'$ compatible with $R_{\text{shell}} \sim 5'$
  - $\Gamma = 2.65 \pm 0.19$
  - $F = 1.8 [1.3-2.4] \%$ Crab (0.5 -10 TeV)

- **Two SNRs, $d \sim 11$ kpc** (Caswell et al. 1975)
  - Age $> 1500$ yrs... AD 393? (Clark et al. 1975)
  - Masers & CO clouds (Reynoso et al. 2000)
  - $\text{rms} = 4' \pm 1'$ compatible with $R_{\text{shell}} \sim 5'$
  - $\Gamma = 2.30 \pm 0.13$
  - $F = 2.8 [2.2-3.6] \%$ Crab (0.5 -10 TeV)

Lots of « sources » in between...!

Aharonian et al. (2006)

HESS J1745-303

Accelerator (i.e. SNR) – target (i.e. MC)
Delayed VHE $\gamma$s from MC as a probe of Galactic PeVatrons (Gabici et al. 2007a,b)
Galactic diffuse VHE emission

Milagro survey of the Northern sky (Abdo et al. 2007a,b & 2008)

<table>
<thead>
<tr>
<th>Object</th>
<th>Location (1, b)</th>
<th>Error&lt;sup&gt;a&lt;/sup&gt; Radius (deg)</th>
<th>Significance&lt;sup&gt;b&lt;/sup&gt; pre-trials</th>
<th>Significance&lt;sup&gt;b&lt;/sup&gt; post-trials</th>
<th>Flux&lt;sup&gt;c&lt;/sup&gt; at 20 TeV $\times 10^{-15}$ TeV$^{-1}$cm$^{-2}$s$^{-1}$</th>
<th>Extent Diameter (deg)</th>
<th>Counterparts (References)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>184.5, −5.7</td>
<td>0.11</td>
<td>15.0</td>
<td>14.3</td>
<td>10.9 ± 1.2</td>
<td>-</td>
<td>Crab</td>
</tr>
<tr>
<td>MGRO J2010+37</td>
<td>75.0, 0.2</td>
<td>0.19</td>
<td>10.4</td>
<td>9.3</td>
<td>8.7 ± 1.4</td>
<td>1.1° ± 0.5°&lt;sup&gt;d&lt;/sup&gt;</td>
<td>GEV J2020+3658,</td>
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<td>PWN G75.2+0.1, (1)</td>
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<tr>
<td>MGRO J1908+66</td>
<td>40.4, −1.6</td>
<td>0.24</td>
<td>8.3</td>
<td>7.0</td>
<td>8.8 ± 2.4</td>
<td>&lt; 2.0°(90%CL)</td>
<td>GEV J1907+6557,</td>
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<td>SNR G19.5+0.5</td>
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<tr>
<td>MGRO J2031+41</td>
<td>50.3, 1.1</td>
<td>0.47</td>
<td>6.6</td>
<td>4.9</td>
<td>9.8 ± 2.9</td>
<td>3.0° ± 0.9°&lt;sup&gt;e&lt;/sup&gt;</td>
<td>GEV J2035+8214,</td>
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<td></td>
<td>TEV J2052+413 (2,3)</td>
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<td>C1</td>
<td>77.5, −3.9</td>
<td>0.24</td>
<td>5.8</td>
<td>3.8</td>
<td>3.1 ± 0.6</td>
<td>&lt; 2.0°(90%CL)</td>
<td>-</td>
</tr>
<tr>
<td>C2</td>
<td>76.1, −1.7</td>
<td>a</td>
<td>5.1</td>
<td>2.8</td>
<td>3.4 ± 0.8</td>
<td>-</td>
<td>Gemeni</td>
</tr>
<tr>
<td>C3</td>
<td>195.7, 4.1</td>
<td>0.40</td>
<td>5.1</td>
<td>2.8</td>
<td>6.9 ± 1.6</td>
<td>2.8° ± 0.8°&lt;sup&gt;f&lt;/sup&gt;</td>
<td>GEV J2227+6196</td>
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<tr>
<td>C4</td>
<td>105.8, 2.0</td>
<td>0.52</td>
<td>5.0</td>
<td>2.6</td>
<td>4.0 ± 1.3</td>
<td>3.4° ± 1.7°&lt;sup&gt;g&lt;/sup&gt;</td>
<td>SNR G196.6+2.9</td>
</tr>
</tbody>
</table>
H.E.S.S. versus Milagro: sources or diffuse emission?

5 HESS sources
30° < l < 65°
-2° < b < 2°

HESS J1848-010
HESS J1912+101
HESS J1857+026
HESS J1858+020
IGR J18490-0000
H.E.S.S. versus Milagro: sources or diffuse emission?

> 20% of the Milagro diffuse emission is due to unresolved sources... detected by HESS

Compatible with the expectations of Casanova & Dingus (2008)

But need of uniform survey...

Chaves et al. HESS (2008)
Concluding remarks

More than 60 VHE Galactic sources

Madrid & Macchetto (2009)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Facility</th>
<th>Citations</th>
<th>Participation</th>
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<tbody>
<tr>
<td>1</td>
<td>SDSS</td>
<td>1892</td>
<td>14.3%</td>
</tr>
<tr>
<td>2</td>
<td>Swift</td>
<td>1523</td>
<td>11.5%</td>
</tr>
<tr>
<td>3</td>
<td>HST</td>
<td>1078</td>
<td>8.2%</td>
</tr>
<tr>
<td>4</td>
<td>ESO</td>
<td>813</td>
<td>6.1%</td>
</tr>
<tr>
<td>5</td>
<td>Keck</td>
<td>572</td>
<td>4.3%</td>
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<tr>
<td>6</td>
<td>CFHT</td>
<td>521</td>
<td>3.9%</td>
</tr>
<tr>
<td>7</td>
<td>Spitzer</td>
<td>469</td>
<td>3.5%</td>
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<tr>
<td>8</td>
<td>Chandra</td>
<td>381</td>
<td>2.9%</td>
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<tr>
<td>9</td>
<td>Boomerang</td>
<td>376</td>
<td>2.8%</td>
</tr>
<tr>
<td>10</td>
<td>HESS</td>
<td>297</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

Let's keep on doing (HE-)VHE astronomy with Fermi, H.E.S.S.-II, Magic-II, VERITAS...

Uniform disk ($\alpha = -1$)

Spiral arms ($\alpha = -0.6$)
Shell-type SNRs

Loss-limited filaments?

Magnetically-limited filaments?
(Pohl, Yan & Lazarian 2005)
Some cases in between: CTB complex

Diffuse thermal (~0.7 keV) X-ray emission \( \{v_s > 800 \text{ km/s} ; \text{age} < 5 \text{ kyr}\} \) & \( n \sim 0.5 \text{ cm}^{-3} \)

No X-ray PWN nor NT X-rays from the shell

Hadronic scenario \( \rightarrow \eta \sim 0.4 \ E_51 \ d_{7 \text{kpc}}^2 \ n_{0.5}^{-1} \)

Diffuse thermal (~0.8 keV) X-ray emission

Extended NT X-ray emission but no PSR

No NT X-rays from the shell

« Relic » VHE PWN?