H.E.S.S. Observations of SNRs and PWNe

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for the H.E.S.S. Collaboration

SNR/PWN in the Chandra era, Boston, 8-10 July 2009
Young Shell type SNRs
RX J1713.7-3946 & Vela Junior

Angular resolution < 0.1° → morphology resolved

- Discovery by ROSAT All-Sky Survey
- X-ray emission mostly non-thermal
- Detection by H.E.S.S.
Gamma-ray Spectra of the 2 SNRs

- Pure power-law ruled out
- Significant gamma-ray emission approaches 100 TeV
  - 4.8σ beyond 30 TeV!
- Primary particle energies:
  - Hadronic scenario:
    \[ E_{\text{proton}} \sim 200 \text{ TeV} \]
  - Leptonic scenario:
    \[ E_e \sim 100 \text{ TeV} \]

- Lower statistics: \( E_{\text{max}, \gamma} \sim 20 \text{ TeV} \)
- Index \( \sim 2.24 \)
- Indication of cut-off

\[ \text{Flux (cm}^2\text{s}^{-1}\text{TeV}^{-1}) \]

\[ \text{Power-law } \Gamma = 2.24 \pm 0.04 \text{ with indication of a cutoff?} \]
Spatially resolved spectra of RX J1713

No significant change in spectral shape was detected in VHE
Large variation observed in X-rays...using different regions in size and shape

TeV Photon Index

X-ray Photon Index


X-ray vs gamma-ray correlation on the same scale

Smoothed with the HESS PSF

Energy band:
0.5-5 keV
Astrophysical background subtracted

The spatial variation of the spatial index are smeared out when using larger extraction regions.

Mean X-ray photon index slightly higher than the gamma-ray index

Bright regions are brighter in X-rays than in gamma-rays (non linear correlation)

Acero et al., arXiv:0906.1073
Primary population: electrons?

- Need about 8 \( \mu G \) B field to match flux ratios
- Simplest electronic models don’t work well:
  - steep spectrum in conflict with radio flux
  - Very large \( E_{\text{max}} \) and low B can hardly co-exist in standard models

- Simple one-zone model
- Electrons & protons injected with the same spectral shape
- Energy losses + escape of particles out of the shell taken into account

Power-law index = 2.2 at injection level

Power-law index = 2.4 at injection level
Primary population: protons?

- Assuming that RX J1713 was a core collapse SN which exploded into a very diluted bubble created by the wind of a massive progenitor star
- Explosion energy $= 1.8 \times 10^{51}$ erg
- Proton injection rate $= 3 \times 10^{-4}$
- Bubble density $= 10^{-2}$ cm$^{-3}$ & ISM density $= 300$ cm$^{-3}$

- Magnetic field $= 126 \, \mu$G in agreement with the lower limit derived from the narrow filament resolved by XMM (65 \, \mu G)
- But XMM-Newton limit on thermal X-rays implies a very low density in the remnant (0.02 cm$^{-3}$) $\Rightarrow$ needs a bubble to make such hadronic model works in terms of energetics

First non-thermal hard X-ray SNR (1995)

Shell-type supernova

distance = 2.2 ± 0.08 kpc

$N_H \approx 0.05 \text{ cm}^{-3}$

XMM-Newton (Acero et al. 2007)

HESS 18hrs (2tels) + 6hrs (4tels):
=> Upper Limit
H.E.S.S. detection of SN 1006

Continued obs: 130hrs live time
Detection: $9.3\sigma$ in the NE and $8.7\sigma$ in SW

- Model combined analysis
- 2 pre-defined regions from XMM-Newton smoothed map: 80% of total emission
H.E.S.S. Spectral analysis of SN 1006

- Spectra compatible with straight power-law for both regions

- $\Gamma \sim 2.4$ and Flux $\sim 1\%$ Crab $\Rightarrow$ SN1006 is one of the faintest VHE source

- Similar excess events and spectra in both regions attesting the bipolar morphology of the remnant in the TeV range $\Rightarrow$ injection most efficient in the polar cap regions

- Leptonic scenario $\Rightarrow$ $B \sim 30 \, \mu G$

- Hadronic scenario $\Rightarrow$ $W_{\text{CR}} \sim 20\% \, E_{\text{SN}}$

<table>
<thead>
<tr>
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<th>$\Phi(&gt;1\text{TeV}) \times 10^{-12}\text{cm}^{-2}\text{s}^{-1}$</th>
<th>$\Gamma$</th>
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<tbody>
<tr>
<td>NE</td>
<td>0.186$\pm$0.024</td>
<td>2.54$\pm$0.15</td>
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<td>SW</td>
<td>0.165$\pm$0.031</td>
<td>2.34$\pm$0.22</td>
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H.E.S.S. Detection of RCW 86

- Complete shell in radio, optical and X-rays
- Possible association with SN185

- Livetime 31 hours, 1546 gamma-ray excess events \((8.5\sigma)\)
- Questions of the morphology cannot be settled with the statistics available at the moment
- Photon index: \(2.54 \pm 0.12 \pm 0.20\)
- Integral flux\((1-10 \text{ TeV}) \sim 10\% \text{ Crab}\)
- No significant cut-off
- Leptonic scenario:
  - IC on CMB photons \(\Rightarrow B \sim 30 \mu\text{G}\)
Galactic gamma-ray sources and PWNe

• Much improved sensitivity of current Imaging Atmospheric Cherenkov Telescopes
• Galactic Plane Survey now extended to the region covering longitudes -80° to 60°
• More than ~60 VHE sources: about half of them are PWNe:
  • Established PWNe
  • Coincident with known energetic pulsar
  • Coincident with known X-ray nebula

Chaves et al. HESS (2008)
Established PWNe
Young PWNe

- Crab, G0.9+0.1, MSH 15-52, G21.5-0.9, Kes 75...
- MSH 15-52: first PWN morphologically resolved in TeV gamma-rays
- G21.5-0.9 / PSR J1833-1034: P=61.8 ms; τ=4.8 kyr; but Age < 1000 yrs; Edot=3.3×10^{37} erg/s \Rightarrow 2^{nd} strongest!
- Kes 75 / PSR J1846-0258: P=324 ms; τ=723 yrs; B_{surf}=4.8×10^{13} G \Rightarrow magnetar limit!
- Both G21.5-0.9 and Kes 75 are particle dominated: B \sim 15 \mu G

See presentation by A. Djannati-Ataï
Established PWNe
Older and offset PWNe

- **Vela X**, nebula of PSR B0833-45
  - Located primarily south of the pulsar
  - Apparently the result of relic PWN being disturbed by asymmetric passage of the SNR reverse shock (e.g. Blondin et al. 2001)
  - Coincident with one sided “jet” (Markwardt & Ogelman, 1995)

See presentation by B. Glück
PWNe with known pulsars &/or X-ray nebula: e.g. HESS J1809-193

- 3600 events detected, 19σ:
  - Significantly extended, south of the Pulsar PSR J1809-1917
  - Power-law with an index of $2.2 \pm 0.1_{\text{stat}} \pm 0.2_{\text{syst}}$
  - Flux of $\sim 1.3 \times 10^{-11}$ erg/cm$^2$/s
- HESS J1809-193, nebula of PSR J1809-1917?
  - Required efficiency $\dot{E}/L \approx 2\%$
  - Strong X-ray nebula detected with Chandra, but extension much smaller
New pulsars coincident with HESS sources

• HESS J1837-069:
  • HESS source detected during the First Galactic Survey; Source extended: $\sigma = 0.22^\circ$
  • Discovery with RXTE of PSR J1838-0655 (P=70.5 ms) with efficiency to power the HESS source of $E_{\text{dot}}/L_\gamma \approx 3\%$ (Gotthelf and Halpern, 2008)
  • HESS emission profile asymmetric relative to pulsar position $\Rightarrow$ support the association (Marandon et al., HDGS, 2008)

• Discovery of PSR J1856+0245 with Arecibo, possibly powering HESS J1857+026, $E_{\text{dot}}/L_\gamma \approx 3\%$ (Hessels et al., 2008)
  • Coincident with unresolved ASCA source AX J185651+0245

• Discovery of Blind search pulsars with Fermi-LAT, for instance the Rabbit in the Kookaburra complex
Time to make population study

See Mattana et al. 2008 & Grenier et al. 2008

\[
\frac{L_\gamma}{L_x} \propto t^{2.2} \quad \frac{L_\gamma}{L_x} \propto \dot{E}^{-1.9}
\]
Conclusions

- HESS has opened a new window for the study of SNRs and PWNe
  - 3 shell-type SNRs (RX J1713, Vela Junior & SN1006) resolved + several detected
  - First time ever spatially resolved spectral study of a gamma-ray source (RX J1713.7-3946)
  - SNR interacting with molecular clouds (eg. W28)
- More than 60 VHE galactic sources, about half of them being PWNe
- Multi-wavelength work, especially in coordination with Fermi and X-ray satellites, can bring new science and help identifying new candidates

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The Galaxy in a new light: Observations of the Fermi-LAT

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for the Fermi-LAT Collaboration
The GLAST Observatory

GBM
Bismuth Germanate Detector
150 keV – 30 MeV

GBM
Sodium Iodide Detector
8 keV – 1 MeV

LAT
20 MeV – 300 GeV

GBM
Bismuth Germanate Detector
150 keV – 30 MeV
Launched from Cape Canaveral on a Delta IIH, 11 June 2008

GLAST was renamed the Fermi Gamma-Ray Space Telescope on August 26, 2008
### Fermi-LAT as a Telescope

<table>
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<th>Years</th>
<th>Ang. Res. (100 MeV)</th>
<th>Ang. Res. (10 GeV)</th>
<th>Eng. Rng. (GeV)</th>
<th>$A_{\text{eff}} \cdot \Omega$ (cm² sr)</th>
<th># $\gamma$-rays</th>
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<tr>
<td>EGRET</td>
<td>1991–00</td>
<td>5.8°</td>
<td>0.5°</td>
<td>0.03–10</td>
<td>750</td>
<td>$1.4 \times 10^6$/yr</td>
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<tr>
<td>AGILE</td>
<td>2007–</td>
<td>4.7°</td>
<td>0.2°</td>
<td>0.03–50</td>
<td>1,500</td>
<td>$4 \times 10^6$/yr</td>
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<tr>
<td><strong>Fermi LAT</strong></td>
<td>2008–</td>
<td>3.5°</td>
<td>0.1°</td>
<td>0.02–300</td>
<td>25,000</td>
<td>$1 \times 10^8$/yr</td>
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- LAT has already surpassed EGRET and AGILE celestial gamma-ray totals.
- Unlike EGRET and AGILE, LAT is an effective All-Sky Monitor whole sky every ~3 hours.
9-month all-sky survey

Fermi-LAT reveals best ever view of the gamma-ray sky!
The Fermi Telescope has found 16 previously unknown pulsars (yellow). It also detected gamma-ray emissions from known radio pulsars (magenta for the 8 MSPs), and from known or suspected gamma-ray pulsars.
Fermi blind search pulsars: the link to SNRs and PWNe

- Detection of 16 new gamma-ray pulsars through blind frequency search: Abdo et al., Science Express, 2nd July 2009
- 5 pulsars likely associated with PWN/SNR:
  - J0007+7303: CTA1
  - J1418-6058 (Kookaburra complex): G313.3+0.1, the Rabbit
  - J1809-2332 (Taz PWN): mixed-morphology type SNR G7.5-1.7
  - J1826-1256 powering the Eel PWN
  - J2021+4026: gamma Cygni SNR
- 2 more plausible associations: J0633+0632 (Monoceros), J1907+0601 (G40.5-0.5)
Fermi view of the Crab Nebula

- Synchrotron component fit with COMPTEL + LAT => cut-off at ~100 MeV
- No cut-off seen with LAT data only for the IC component
- LAT high energy and Cherenkov spectra link up naturally
- Overlaying predictions of Atoyan, A.M. and Aharonian, F.A., 1996, MNRAS, 278, 525 for different nebular mean magnetic fields, the results obtained by the LAT and ground based telescopes are consistent with $100 \mu \text{G} < B < 200 \mu \text{G}$, indicating a magnetic field well beyond the equipartition field in the Crab nebula (300 µG)

![Graph showing energy vs. flux density for different telescopes and magnetic field predictions](image)
An extended source in the W51C region

- $D \sim 6\text{kpc}$, Age $\sim 20000$ yrs
- Molecular cloud interactions
- SNR diameter $\sim 30$ arcmin
- Very recent HESS detection
- Detection with Fermi-LAT! Extended emission beyond the LAT PSF; very large luminosity using 6kpc ($\sim 4 \times 10^{35}$ erg/s)

Star-forming region W51B overlaps with SNR W51C (W51B is likely interacting with SNR W51C)

Fermi LAT counts map: very bright ($>40\sigma$) gamma-ray source

Fermi LAT 2-8 GeV
The W44 region as viewed by Fermi-LAT

- D ~ 3kpc, Age ~20000 yrs
- Molecular cloud interactions
- Spatial extent ~35 arcmin × 26 arcmin
- Spatially coincident with 3EG J1856+0114 but large error circle
- Detection with Fermi-LAT! Extended emission beyond the LAT PSF
Detection of a source in the Vela X region

Using 9 months of survey data with Fermi-LAT and the off-pulse events:
• TS ~80 (i.e. ~9σ) for E > 800 MeV: significant detection
• Good positional agreement with Vela X as seen with 8.4 GHz Parkes radio data
Fermi detects tons of Pulsars!

Clear identification of the Crab Nebula; study of both the synchrotron and inverse compton peaks in the frame of a simple SSC model \(\Rightarrow\) magnetic field smaller than the equipartition field

Fermi-LAT detected significant gamma-ray emission spatially coincident with W51C, W44 and Vela X:

The gamma-ray sources are extended beyond the Fermi-LAT PSF

Detailed spectral analysis, morphological studies (precise measure of extension) as well as multi-wavelength modeling are underway

All detailed results will be reported in the upcoming papers
Vela X: directly located in the Galactic Plane!

All phase Smoothed Counts map ($\sigma=0.3^\circ$)

Off-pulse Smoothed Counts map ($\sigma=0.3^\circ$)
An extended source

Spatially extended!

Smoothed excess map ($\sigma = 0.3^\circ$)
E $> 800$ MeV
Fermi-LAT TS contours (white)

Profile along the Declination axis
Blue: observed counts
Red: Point source simulated at the position of the Vela PSR

Excess map

Profile

PRELIMINARY
Radio, VHE spectrum and Fermi-LAT data for entire PWN suggests presence of two distinct electron populations
- radio-emitting particles may be relic population; higher energy electrons injected by pulsar

Maximum energy of radio-emitting electrons not well-constrained
- this population generates IC emission in GLAST band (consistent with positional agreement and extension)
- upcoming observations will provide strong constraints on this electron population
W51C: an extended source

- Mean surface brightness (2-8 GeV) as a function of distance from the SNR center vs Fermi-LAT PSF (using the energy spectrum obtained with maximum likelihood technique)
SNRs in our Galaxy: 231 (Green et al. 2001) with non-thermal X-ray emission - ~10 TeV emission

Cosmic-ray accelerators?

Best candidates - young SNRs with non-thermal synchrotron X-rays

RX J0852.0-4622

H.E.S.S. PSF

SNR RX J1713.7-3946

TeV emission
Established PWNe from the TeV properties

- **HESS J1825-137**, nebula of PSR B1823-13
  - Large TeV source, offset from the pulsar
  - Smaller X-ray extension
- TeV gamma-ray spectral steepening with distance away from pulsar
  - Consistent with radiative losses of $e^\pm$ accelerated near the pulsar

SNR interacting with molecular clouds
the example of W28

- Mixed morphology SNR
- Distance between 1.8 and 3.3 kpc (Goudis 1976, Lozinskaya 1981)
- Very old remnant: 35 000 to 150 000 years old
- Interaction with a molecular cloud (Wootten 1981) along its North and North-Eastern boundaries

VLA 90cm radio emission
H.E.S.S. results on W28

- Interaction of the remnant with a dense molecular cloud seen in NANTEN CO (J=1-→0) observations
  - Presence of OH masers
  - Energetics compatible with CRs accelerated within the SNR and interacting with the cloud
- Molecular clouds seen also in coincidence with the southern excesses
  - Distances compatible with the SNR
  - Hadronic scenario also possible
- Alternative scenarios possible for the southern emission:
  - Other SNRs, young stars, open stellar cluster