Pulsar Wind Nebulae in $\gamma$-rays: from GeV to TeV energies

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Outline

1. A brief introduction to:
   - Pulsar Wind Nebulae (PWNe)
   - Scientific context

2. Results: GeV & TeV observations of PWNe:
   - Young PWNe
   - Offset/middle-aged PWNe
   - PWN candidates

3. Summary
- **Relativistic particles** ($e^\pm$) **injected by the central pulsar**
- **Ejecta of the supernova swept up**
- **Flow decelerated by the shock**
- **Particles are accelerated at the shock** (Diffusive Shock Acceleration, Resonant cyclotron absorption, etc.) and **radiate**


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GeV/TeV emission mechanisms in PWNe (& SNRs)

Non-thermal photon emission:

- Synchrotron emission
- Inverse Compton scattering
- Bremsstrahlung
- Proton-proton interaction

Credits: J. Hinton
GeV/TeV emission mechanisms in PWNe (& SNRs)

Non-thermal photon emission of \textit{leptonic or hadronic origin}

- Observations in the GeV/TeV range \(\rightarrow\) \textit{disentangle between the radiation processes}
- Multiwavelength observations \(\rightarrow\) \textit{constrain the physical properties of the sources}

![Diagram showing different types of telescopes and energy flux](image)

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Imaging Atmospheric Cherenkov Telescopes

Energy range: few tens of GeV - 80 TeV
Area > $10^4$ m$^2$
Background Rejection > 99%
Angular Resolution ~0.05°

See talk by R. LOPEZ-COTO
See talk by P. BRUN
**Status in the TeV range**

**Improved sensitivity** of current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs)

→ detection of ~145 VHE sources

MAGIC/VERITAS visibility

HESS visibility

TeVCat: [http://tevcat.uchicago.edu/](http://tevcat.uchicago.edu/)

Source Types:
- PWN
- XRB PSR Gamma BIN
- HBL IBL FRI FSRO LBL AGN (unknown type)
- Shell SNR/Molec. Cloud
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Cat. Var. Massive Star Cluster BIN WR

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**Status in the TeV range**

*Improved sensitivity* of current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs)

→ detection of ~145 VHE sources

→ ~60 Galactic VHE sources known

→ ~32 are identified as PWNe, >12 candidates

TeVCat: [http://tevcat.uchicago.edu/](http://tevcat.uchicago.edu/)
**HESS(-I) & the Galactic Plane Survey**

**H.E.S.S. = High Energy Stereoscopic System (Phase I):**
- Four telescopes, 107 m² mirror area each (+ 1)
- Energy threshold: ~ 100 GeV
- Sensitivity: 1% Crab in 25 h
- Field of view (diameter): 5°

**Galactic Plane Survey:**
- Now covering Gal. Long. from -85° to +60°, with -3° < Gal. Lat < 3°

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HESS & the Galactic Plane Survey

Credits: HESS Collaboration
HESS & the Galactic Plane Survey

Credits: HESS Collaboration

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HESS & the Galactic Plane Survey

> 50% of the Galactic VHE sources are PWNe

Credits: HESS Collaboration

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**Status in the GeV range**

Recent launches of the gamma-ray satellites **AGILE** (April 2007) and **Fermi** (June 2008)


→ ~30% unidentified sources

→ ~50% sources close to the Galactic plane

Fermi-LAT (20 MeV – 300 GeV)

AGILE (30 MeV – 50 GeV)
Status in the GeV range

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→ detection of ~1900 GeV sources (2FGL Catalog, arXiv:1108.1435)
→ ~30% unidentified sources
→ ~50% sources close to the Galactic plane
→ already 6 PWNe firmly identified, ~10 PWN candidates + 147 pulsars
**Status in the GeV range**

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Firmly identified PWNe

~6 PWNe

~10 PWN candidates + 147 pulsars

Each PWN or PWN Candidate detected in the GeV range is associated to a VHE source

* Except MSH 11-62

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Why do we detect so few GeV PWNe?

PWN studies (detection, morphological & spectral analyses) require:
- A temporal analysis of the powering pulsar & subtraction of the pulsed component
- A good knowledge of:
  - The diffuse background (spatial & spectral structures in the Galactic diffuse emission)
  - The instrumental point spread function (PSF) varying over the LAT range
    \( \sim 5^\circ \text{ at } 100 \text{ MeV} \rightarrow \sim 0.6^\circ \text{ at } 1 \text{ GeV} \rightarrow \sim 0.2^\circ \text{ at } 10 \text{ GeV} \) (Pass 7)

Pass 8: See talk by C. SGRO
PWN evolution in a nutshell

**Free expansion**

- SNR
- Pulsar
- PWN
- 2-6 kyr

**Reverse shock interaction**

- 20-100 kyr?

**Relic stage**

Credits: S. Klepser

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PWN evolution in a nutshell

1) Young PWNe
2) Middle-aged and offset PWNe
3) PWN candidates
4) Systematic searches for PWNe

Credits: S. Klepser
1. Young PWNe

**GeV-TeV**: Crab Nebula, MSH 15-52, 3C 58

**TeV only**: SNR G0.9+0.1, SNR G21.5–0.9 & Kes 75, HESS J1813–178, SNR G54.1+0.3, Rabbit
The Crab Nebula, the brightest VHE source...

The brightest VHE galactic «steady» source, observed by every Cherenkov experiment & Fermi (Abdo et al, 2010, 708, 1254):

- Γ-ray emission **below 500 MeV** due to synchrotron emission
  → electrons accelerated up to ~1 PeV

- high energy component due to IC (mainly on synchrotron photons)
  → fit of the IC peak at ~53 GeV (using Fermi and MAGIC results)

Aleksic, et al, 2014
... but no more a standard candle


R. Buehler, Fermi Symposium 2011


- Flux increase by ~5-6 during 2009, 2010, March 2013 flares, by ~30 during 2011 flare!

- Compact emission region < 0.0004 pc ~ 0.04'' (for D<4)

→ Emission from the inner nebula
The PWN 3C 58

Associated to the energetic pulsar PSR J0205+6449
(\( \dot{E} = 2.7 \times 10^{37} \) erg/s, \( \tau_{\text{char}} = 5.4 \) kyr, \( P = 65.7 \) ms)

- Angular size: 6’ x 9’
- Distance: 2 kpc
- Age: < 1 kyr?

Recent discovery of gamma-ray emission by:
- MAGIC (Aleksic et al, 2014)

Spectral modeling → association with SN 1181 C.E. still viable
2. Middle-aged and offset PWNe

**GeV-TeV**: Vela X, HESS J1825-137, HESS J1857+026

**TeV only**: HESS J1303-631, HESS J1356-645, HESS J1837-069

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The puzzling Vela X

- Associated with the Vela Pulsar (d = 290 pc)
- Offset from the pulsar
- Morphology:
  - Radio & HE gamma-rays: Halo (2° x 3°)
  - X-rays & VHE: Cocoon (length < 1°)

- Multiwavelength spectrum:


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... and even more puzzling!

In the GeV range (Grondin et al., 2013):
- Using a lower energy threshold 
  → unveils an energy-dependent morphology
  - 300 MeV – 1 GeV (red) : HE emission matches the radio halo (yellow contours)
  - Above 1 GeV (green) : correlates with the Southern wing of the radio (as reported in the 1st Fermi paper)

In the TeV range (Abramowki et al., 2012):
- Deeper observations by HESS:
  - Brighter TeV emission still correlates with X-rays
  - Fainter emission extends beyond the X-ray cocoon
    → emission consistent with the radio halo ?!? 
  - Uniform γ-ray spectrum between the inner and outer regions (peaks at ~10 TeV)

What is the origin(s) of the GeV and TeV emission?

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3. PWN candidates

SNR CTA1:
- PWN candidate detected by VERITAS
- Pulsar discovered by Fermi
+ Off-pulse emission (PWN?)

=> PWN observed in GeV and TeV?

VERITAS excess map
4. Searching for TeV PWNe in the GeV range

Searching for PWNe with Fermi:


b. at high energy (10 GeV)
   - Coincident with TeV sources
   - $|b| < 5^\circ$
   - Removing SNRs, Gal. Center, Crab & Vela-X

$=> 58$ regions analyzed

a. Searches for PWNe behind pulsars

Some famous candidates searched in the off-pulse window of gamma-ray pulsars:

- Kookaburra & Rabbit
- MGRO J1908+06
- HESS J1356-465
+ others (Ackermann et al, 2011, 726, 35)

More data are required to detect any GeV emission from the PWN

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b. Searches for PWNe above 10 GeV

Detection of K3/Kookaburra above 10 GeV

- Kookaburra complex (Roberts et al. 1999): contains 2 PWNe detected at TeV:
  - HESS J1420-607 / K3
  - HESS J1418-609 / Rabbit

- Searches for TeV PWN emission above 10 GeV (Acero et al., 2013):
  - emission above 10 GeV: from the powering pulsars?
  - LAT GeV emission on Rabbit vanishes above 30 GeV; but still bright signal coming from K3
  - potential PWN detection of K3 by the LAT
    (detected also at E>100 GeV by Neronov & Semikoz, 2012)
**Summary**

**GeV:**
- Already 6 PWNe clearly identified + ~10 PWNe candidates
- Efficiency < 10% of the spin-down power of the pulsar is required to explain the luminosity above 100 MeV

**TeV:**
- PWNe: largest population of Galactic TeV sources
- Many of the unidentified sources might be PWNe

**GeV and TeV PWNe preferentially associated to energetic and young pulsars (\(\dot{E} > 10^{35} \text{ erg/s}\))**

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R. Rousseau, Fermi Symposium 2012

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The GeV-TeV connexion

Detection of GeV & TeV gamma-ray PWNe:
- a leptonic (IC scattering) origin for the high energy component of the spectrum is favored in each case
- Vela X is the first case where the injection of 2 leptonic components is suggested by multi-wavelength data

TeV astronomy has opened a new observational window for the study of PWNe, giving a more direct view of the accelerated particle population

Fermi gives a more complete overview of energetic pulsars in our Galaxy → improving PWN identification (especially at TeV) and population studies in the future
PWNe in the GeV sky

HESS J1857+026
HESS J1837-0657
MSH 11-62
HESS J1023-575
Crab Nebula

K3 & HESS J1356+635

3C 58

SNR CTA 1

HESS J1825-137
HESS J1640-465
MSH 15-52
Vela X

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Thank you for your attention