Supernova Remnants and Pulsar Wind Nebulae observed in TeV $\gamma$ rays

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Particle acceleration by stellar remnants

Gamma-ray astronomy at energies $\sim$100 MeV to $\sim$10 TeV:
rich evidence of particle acceleration in ...

- supernova remnants
- pulsar wind nebulae
- young and “rejuvenated” pulsars

Powered by
- explosion energy
- pulsar rotation
- strong EM fields; accretion

Acceleration at
- shock front
- shocked wind
- polar cap, slot gap?

Time scale after death of star
- few kyr
- few 10 kyr
- few 100 kyr – Myr

Adapted from F. Acero
Particle acceleration by stellar remnants

Gamma-ray astronomy at energies ~100 MeV to ~10 TeV: rich evidence of particle acceleration in ...

... supernova remnants ... pulsar wind nebulae

SN 1006 Crab Nebula

Major Galactic TeV $\gamma$-ray source classes:
- 5 shell-type, 9 interacting SNRs, 33 PWNe
  - Flux and composition (hadr./$e^{\pm}$ ?)
  - Max. energy (~1 PeV ?)

... young and “rejuvenated” pulsars

→ talk by F. Calore

Important Fermi source class
- Release & acceleration?
- Contribution to diffuse $\gamma$ flux?
Supernova remnants

Young SNRs

- Efficient particle acceleration in the shell
- Spectral features well reproduced by mixed hadr./lept. models

Older SNRs

- Hadronic scenario favoured
- Electron acceleration less efficient

- $\pi^0 \rightarrow 2\gamma$ enhanced by mol. clouds:
  - interaction w/ shell or
  - illumination by escaping CR flux

H.E.S.S. coll., Acero et al. (2010)

Multi-band X-ray image (Chandra; F. Winkler 2013)
Pulsar wind nebulae: synopsis

“\textit{A bubble of shocked relativistic particles, produced when a pulsar's relativistic wind interacts with its environment}”

(Gaensler & Slane, 2006)
Pulsar wind nebulae: synopsis

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Crab Nebula
(infrared, optical, X-rays)

Crab Nebula

Pulsar wind magnetized outflow

wind termination shock

non-thermal nebula

R_{PWN} \sim \text{several pc}

R_{\text{wind}} \sim 0.1 \text{ pc}

\pm e^+ \pm e^-

Synchrotron Inv. Compton

\log_{10} E^2 (\text{et/cm}^2)
Pulsar wind nebulae: evolution

I. Free expansion

- Simplest phase
- $R \sim t^{6/5}$
- Well studied, e.g. via Crab
  Kennel & Coroniti 1964, Martín++ 2012, ...

II. Reverse shock interaction

- Depends on SNR development
- Oscillatory reverberations
- Analytically: $R \sim t^{0.3}$
- Only over-idealized and/or numerical models
  e.g. Swaluw++ 2001, 2004, ...

III. Relic phase

- Even more influenced by SNR evolution, surroundings
- $R \sim ??$
- Only case-by-case studies

2-6 kyr

20-100 kyr?
Pulsar wind nebulae in TeV $\gamma$ rays

- Weakest TeV PWN ever detected: $L_{>1\text{TeV}} \sim 0.65\%$ Crab, $\sim 10^{-5} \dot{E}$
- Probably young ($\tau_c \sim 5$ kyr)
- TeV source coincides with pulsar, size not resolved ($r < 4$ pc)

- Middle-aged ($\tau_c \sim 21$ kyr, $r \sim 35$ pc)
- “Crushed” shape (asymmetry, displacement)
- Synchr. burn-off of high-E particles
PWN population study: aims

• Uniform analysis of TeV sources, selection and evaluation of candidates
• Upper limits for non-detections

Observational data

• Link between properties of pulsar and TeV PWN?
• Benchmark common perceptions of PWN evolution

Interpretation
PWN population study: ingredients

(1) H.E.S.S. Galactic Plane Survey
~2800 h obs. of the inner Galaxy (2004-13)
better than 2% Crab sensitivity
discovery of ~60 new sources
→ Position, size, $F(1-10 \text{ TeV})$

(2) ATNF Pulsar Catalogue
> 2000 pulsars (radio, X, γ)
→ Position, P, Pdot, Edot, $\tau_c$, d
PWN population study: methods

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Association & selection of candidates

HGPS + ATNF catalogs
(w/o SNR, GC Binaries, AGN)

TeVCat
online catalog of ~150 VHE \(\gamma\)-ray sources

Previously associated

Externals

New candidates

Pulsars for limits

● Uniform analysis of TeV sources, selection and evaluation of candidates

● Upper limits for non-detections

● Link between properties of pulsar and TeV PWN?

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- Previously associated
- Externals
- New candidates
- Pulsars for limits

Population plots
relating PSR to TeV properties

- Common trends?
- Theory expectations?
- Simple leptonic modeling
- Plausibility of candidates
Correlation of TeV sources and pulsars

(a) energy-dep. detection fraction

(b) angular separation criterion

No correlation beyond chance coincidences below $\sim 10^{35}$ erg/s

Preliminary

High-Edot pulsars: TeV signal within $\sim 0.5^\circ$

Klepser et al., arXiv:1307.7905
Carrigan et al., arXiv:0709.4094
Selection of PWN candidates

S. Klepser et al., arXiv:1307:7905

• Most PWNe likely in reverse shock interaction phase
• Candidates: more evolved
How far can we reach out?

- PWNe trace close-by spiral arms
- Average distance: ~5 kpc
- Exposure covers ~1/4 of the Milky Way

Preliminary

1% of Crab luminosity > 1 TeV

Graphic: C. Deil, S. Klepser
Evolutionary trends

- $R_{\text{PWN}} \sim t^{0.3}$ as a rough guideline, but large scatter due to surrounding medium or SNR interaction
- Good for evaluating candidates

- Compares accumulated $e^\pm$ population with momentary energy output of pulsar
Evolutionary trends

- $R_{\text{PWN}} \sim t^{0.3}$ as a rough guideline, but large scatter due to surrounding medium or SNR interaction
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- Compares accumulated $e^\pm$ population with momentary energy output of pulsar
- Time-dependent one-zone model based on M. Mayer et al., arXiv:1202:1455 (added free expansion phase)
Summary & outlook

- VHE $\gamma$-rays allow to study most powerful particle accelerators in the Galaxy

- Data quality & quantity supports cumulative studies: SNRs, PWNe
  - **PWN population**: biggest (& rather diverse) Galactic source class
  - Many **UNID** sources might be ageing PWNe
  - Modeling: need better understanding of evolved PWNe …

… in particular for the leap ahead with CTA
References

Selection of recent reports on progress of Galactic TeV survey & source census:

- **H.E.S.S. Galactic Plane Survey**
  - Carrigan et al., *Charting the TeV Milky Way*, arXiv:1307.4868

- **PWN population study**

- **SNR population study**

  - Aharonian, *Gamma rays from supernova remnants*, p. 71
  - Acero et al., *Gamma-ray signatures of cosmic-ray acceleration, propagation, and confinement in the era of CTA*, p. 276
  - de Ona Wilhelmi et al., *Prospects for observations of pulsars and pulsar wind nebulae with CTA*, p. 287
Supplementary slides
Galactic Sources of VHE $\gamma$ rays

~90 sources of VHE $\gamma$ rays ($E > 100$ GeV) in the Milky Way known today*:

*) tevcat.uchicago.edu, Aug. 2014
The TeV gamma-ray sky today

Source Types
- PWN
- Binary XRB PSR Gamma BIN
- HBL IBL FRI FSPQ Blazar LBL AGN (unknown type)
- Shell SNR/Molec. Cloud Composite SNR
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

Http://tevcat.uchicago.edu
Old PWNe as unidentified VHE $\gamma$-ray sources?

Comparison of X-ray and VHE $\gamma$-ray luminosities for several identified PWNe

Time-dependent leptonic model of broad-band emission for a generic PWN

Mattana et al. (2009)

PWN population study: potential selection bias

Closer objects tend to have larger lower efficiencies and smaller extensions

- Far away sources need to be more efficient in order to get detected
- Clipping of large, nearby sources due to limited field of view?
- Far, small sources cannot be resolved → upper limits on extension

S. Klepser et al., ICRC'13
Why study (multi-wavelength) properties of PWNe?

• We can learn something about …
  – *the pulsar*:
    spin-down characteristics/history, proper motion, …
  – *the pulsar wind*:
    composition, energetics, geometry, termination shock, …
  – *the ambient medium*:
    local density/homogeneity, magnetic field, …

• Increasing sample of detected PWNe allows to
  – identify general properties
  – investigate various evolutionary stages

Multi-wavelength observational data + Detailed modeling
Imaging Atmospheric Cherenkov Technique

for ground-based gamma-ray detection ($E_\gamma \sim 100$ GeV … 10 TeV)

Air shower observed simultaneously by multiple telescopes
What is a Pulsar Wind Nebula?

Aharonian, Bogovalov & Khangulyan (2012)
http://www.nature.com/nature/journal/v482/n7386/images/nature10793-f2.2.jpg
Pulsar Wind Nebulae: Overview

Hydrodynamical simulations, Van der Swaluw, Downes & Keegan (2004)
Time-dependent leptonic model of non-thermal emission from PWNe

Characteristic age and spin-down timescale

\[ \tau_c = \frac{P}{2\dot{P}} \quad \tau_0 = \frac{2\tau_c}{n-1} \left( \frac{P_0}{P} \right)^{n-1}, \]

Time evolution of energy output and magn. field (see Zhang et al., 2008):

\[ \dot{E}(t) = \dot{E}_0 \left( 1 + \frac{t}{\tau_0} \right)^{\frac{n+1}{n-1}} \quad B(t) = \frac{B_0}{1 + (t/\tau_0)\alpha} + B_{\text{ISM}} \]

Cooling processes (see Zhang et al., 2008):

\[ \frac{dN_{\text{cooled}}(E, t)}{dE} = \frac{dN}{dE}(E, t - \delta t) \cdot \exp \left( -\frac{\delta t}{\tau_{\text{eff}}(E, t)} \right) \]

\[ \tau_{\text{syn}}(E, t) = 12.5 \cdot \left[ \frac{B(t)}{10 \mu G} \right]^{-2} \cdot \left[ \frac{E}{10 \text{ TeV}} \right]^{-1} \quad \text{kyr} \]

\[ \tau_{\text{esc}}(E, t) = 34 \cdot \left[ \frac{B(t)}{10 \mu G} \right] \cdot \left[ \frac{E}{10 \text{ TeV}} \right]^{-1} \cdot \left[ \frac{R(t)}{1 \text{ pc}} \right]^2 \quad \text{kyr} \]

PWN evolution (Gaensler & Slane, 2006):

\[ R(t) \propto \begin{cases} 
  t^{6/5} & \text{for } t \leq \tau_0 \\
  t & \text{for } \tau_0 < t \leq \tau_{\text{RS}} \\
  t^{3/10} & \text{for } t > \tau_{\text{RS}}.
\end{cases} \]

free expansion

after RS interaction
Dissecting the broad-band SED into contributions from different epochs

Generic middle-aged PWN:

\[ P_0 = 30 \text{ ms}, \ P = 100 \text{ ms} \]
\[ B_0 = 50 \mu \text{G} \]
\[ \dot{E} = 2.8 \cdot 10^{36} \text{ erg/s} \]

Mayer, Brucker, Holler, Jung, KV, Stegmann: Predicting the X-ray flux of evolved pulsar wind nebulae based on VHE gamma-ray observations, arXiv:1202:1455
Supernova Remnants

- Paradigm of galactic cosmic rays ($E \leq 10^{15}$ eV): young SNRs as acceleration sites (‘PeVatrons’?)
- Both high-energy hadrons ($p$, nuclei) and leptons ($e^\pm$) can be present → VHE $\gamma$-ray production via $\pi^0$ decay or inverse Compton scattering

SN 1006

- TeV $\gamma$-rays coincident with non-thermal X-rays from the shell
- Spectral energy distribution well reproduced by mixed hadronic-leptonic model