Pulsar wind nebulae: The VHE – X-ray connection

HESS = High Energy Stereoscopic System
H.E.S.S.: High Energy Stereoscopic System

Four twelve meter optical dishes
Khomas Highlands (Namibia)
1800 above sea level
Start of full operation end of 2003

H.E.S.S. collaboration:

MPI für Kernphysik, Heidelberg
Humboldt Univ. Berlin
Ruhr-Univ. Bochum
Univ. Hamburg
Landessternwarte Heidelberg
LLR, Ecole Polytechnique, Palaiseau
LPNHE, Univ. de Paris VI-VII
PCC, College de France, Paris
Observatoire Paris-Meudon, LUTH
CEA Saclay
Univ. de Grenoble
Univ. Montpellier II
CESR Toulouse
Durham Univ.
University of Leeds
Dublin Inst. for Adv. Studies
Nicolaus Kopernikus Astr. Center, Warsaw
Jagiellonian University, Cracow
Institute of Nuclear Physics, Warsaw
Space research center, Warsaw
Charles Univ., Prag
Yerewan Physics Inst.
North-West Univ., Potchefstroom
Univ. of Namibia, Windhoek
Univ. Tübingen
H.E.S.S. event reconstruction parameters:

- Primary direction: < 0.1°
- Field of view: 3° FWHM
- Shower core: 10m → Energy resolution: 15%
- Energy range: 0.1–100 TeV

Cherenkov light from shower particles

Photo: © Philippe Plailly
THE VHE (>100 GeV) Galactic plane from the HESS GP survey
THE VHE (>100 GeV) Galactic plane from the HESS GP survey
Let’s blank out:

• SNR shells: RXJ 1713-3946, Vela Jr, RCW 86
• Binaries: LS 5039, PSR B1259-63
• Stellar cluster association: HESS J1023-575 (Westerlund 2)
• Molecular cloud associations (confirmed and likely): Galactic ridge, HESS J1745-303, HESS J1800-240 (W28 A), HESS J1834-087 (W41)
• For several of the remaining sources, a pulsar wind nebula (PWN) identification is certain
• For the vast majority of the rest, a PWN scenario is at least possible
Overview

• Some general statements about the relation between X-ray and VHE pulsar wind nebulae

• Young vs. middle-aged and relic PWN

• Pevatrons and INTEGRAL

• Identification problem of large-offset VHE PWN

• Underluminous X-ray PWN and associated issues

Warning: totally biased towards VHE-detected PWN
Geometry of a pulsar wind (nebula)

- Neutron star
- Cold, non-emitting flow
- Acceleration of particles at termination shock
- Visible (i.e. emitting) pulsar wind nebula
- Possibly interaction with surrounding SNR (e.g. reverse shock)
X-ray emitting PWN: sample study

Chandra PWN review, Kargaltsev & Pavlov, astro-ph/0801.2602
X-ray emitting PWN: sample study

\( \varepsilon \) or \( \eta \): Efficiency of current pulsar energy loss into given observation band

Large scatter of X-ray synchrotron efficiencies

But fairly good correlation between nonthermal magnetospheric and PWN emission

Chandra PWN review, Kargaltsev & Pavlov, astro-ph/0801.2602
“Usual” X-ray PWN seen with Chandra

Tori and bow shocks/tails reflect pulsar geometry resp. motion
This is not what will be dealt with in this talk
Several firmly identified VHE pulsar wind Nebulae (PWN)

Many VHE PWN candidates

Why identified:
• known pulsar
• morphology matches with X-ray PWN

Most VHE PWN are
• extended
• displaced from the pulsar
Cosmic microwave background ... 

... serves as homogeneous target for Inverse compton scattering of electrons

Credit: WMAP Science Team
In addition, stellar and dust radiation fields can boost IC emission.

WMAP Ka (Thermal and nonthermal)
Stellar and dust photon fields are hard to access (esp. 3-D)
The young Crab Nebula (1000 years)

- compact source, high B-field (160 µG) →
  - high synchrotron efficiency, IC emission comparatively low
  - synchrotron photons produce relevant target field for IC (“SSC”)
→ IC coupled to B-field again
The young Crab Nebula (1000 years)}
The young Crab Nebula (1000 years)

Extended pulsar wind nebulae from middle-aged pulsars
• are simpler because IC scattering off external, in principle well known target photon fields
• are much more common…
... or $F_{\text{VHE}} / F_X$: a widely used diagnostic tool useful for investigating VHE – X-ray source associations


<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>$f_\gamma / f_X$</th>
<th>Extended in TeV?</th>
<th>X-Ray Counterpart</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSI +61 303</td>
<td>HMXB/μ-quasar</td>
<td>0.8</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>LS 5039</td>
<td>HMXB/μ-quasar</td>
<td>0.7</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>PSR B1259–63</td>
<td>HMXB/pulsar</td>
<td>0.4</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>HESS J1634–472</td>
<td>HMXB/NS?</td>
<td>0.03–125</td>
<td>Yes?</td>
<td>IGR J16358–4726?</td>
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<tr>
<td>HESS J1632–478</td>
<td>HMXB?</td>
<td>0.2</td>
<td>Yes?</td>
<td>IGR J16320–4751</td>
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<tr>
<td>1ES 1218+30.4</td>
<td>BL Lac</td>
<td>0.3</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Mrk 421</td>
<td>BL Lac</td>
<td>2.0</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>RX J1713.7–3946</td>
<td>SNR</td>
<td>0.075</td>
<td>Yes</td>
<td>G347.3–0.5</td>
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<tr>
<td>G266.6–1.2</td>
<td>SNR</td>
<td>0.6</td>
<td>Yes</td>
<td>Vela Junior</td>
</tr>
<tr>
<td>Crab</td>
<td>PWN</td>
<td>0.008</td>
<td>No</td>
<td>Crab PWN</td>
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<tr>
<td>HESS J1825–137</td>
<td>PWN</td>
<td>3.4</td>
<td>Yes</td>
<td>B1823–13 PWN</td>
</tr>
<tr>
<td>MSH 15–52</td>
<td>PWN</td>
<td>0.27</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Vela X</td>
<td>PWN</td>
<td>0.6</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>G0.9+0.1</td>
<td>PWN?</td>
<td>0.1</td>
<td>No?</td>
<td>Yes</td>
</tr>
<tr>
<td>HESS J1804/B1800–21^d</td>
<td>PWN</td>
<td>100</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>HESS J1804/Ch1^e</td>
<td>PWN?</td>
<td>30</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>HESS J1804/Ch2^f</td>
<td>PWN?</td>
<td>50</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>HESS J1804/Diff^g</td>
<td>SNR?</td>
<td>$\geq$4</td>
<td>Yes</td>
<td>Yes</td>
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</tbody>
</table>
Lifetime of VHE-emitting electrons

from Aharonian et al., A&A 460, 2006

\[ \tau_{VHE} \approx 3.1 \times 10^5 \left( \frac{w_r}{\text{eV cm}^{-3}} \right) \left( \frac{E}{1 \text{ TeV}} \right)^{-1} \text{ years} \]

\[ w_r = \eta w_{\text{ph}} + 0.025 \text{ eV cm}^{-3} \left( \frac{B}{\mu \text{G}} \right)^2 \]

\( \eta \) normalisation factor due to KN suppression

\( W_{\text{ph}} \) energy density in photon fields (CMB, IR, starlight)

→ For low B-fields, the lifetime of VHE-emitting electrons can greatly exceed the lifetime of the X-ray synchrotron emitting (higher-energy) electrons

→ The VHE PWN reflects the injection evolution of the pulsar
HESS J1640-465: a “relic” PWN scenario

G21.5-0.9, Kes 75: Crab companions?

G21.5-0.9

Chandra

Credit: NASA/CXC/Manithoba/Matheson & Safi-Harb

Edot = $3.3 \times 10^{37}$ erg s$^{-1}$

$\sim 1000$ years ($\ll t_c$)


Kes 75

Chandra

Credit: NASA/CXC/GSFC


Edot = $8 \times 10^{36}$ erg s$^{-1}$

$\sim 800$ years ($\approx t_c$)

Magnetar-like behaviour

Ng et al., astro-ph/0804.3384

HESS coll., Djannati-Atai et al.

astro-ph/0710.2247

$F_X / F_{VHE} \sim 30$

$\rightarrow B \sim 15\mu$G

$F_X / F_{VHE} \sim 10$

$\rightarrow B \sim 10\mu$G

Below equipartition B-fields
Vela-X: a middle-aged PWN

ROSAT contours: extended X-ray synchrotron(?) nebula

Chandra: compact X-ray nebula

Color map: H.E.S.S.: VHE IC nebula

VHE spectrum (peak!) interpreted as IC scattering
→ $E_{\text{nonth}} \sim 2 \times 10^{45}$ erg

Caveat:
→ this isn’t the entire PWN (as seen in radio)
→ sensitivity limited?
VHE + X-rays in case of a hadronic source

Energy flux
$E^2 \, dn/dE$

X-rays
electron synchrotron $\sim B^2$

TeV
electron IC $\sim$ ph.-field

proton: $\pi^0$

high B field ($>10^6 \, \mu G$)

IC $\sim B^{-2}$

Photon energy
Vela X: nucleonic PWN?

- Debate still somewhat open
- Some criticism on the hadronic scenario
- In this talk, the standard view of leptonically-dominated PWN is adopted
- (hadronically mediated acceleration)
“Relic” pulsar wind nebulae

HESS J1825-137: Identification with X-ray PWN G 18.0-0.7

PSR J1826-1334

XMM-Newton

LS 5039
Aharonian et al. (HESS coll.)
A&A 460, 2006
Archetype for a TeV – X-ray PWN association

HESS J1825-137:
Identification (mainly) by TeV spectral imaging

Aharonian et al. (HESS coll.)
A&A 460, 2006
Asymmetric VHE Pulsar Wind Nebulae

"Crushed Plerions"
Blondin et al., 2001

Offset VHE PWN
+ IC electron lifetime larger than synchrotron lifetime
+ larger particle injection efficiency in the past

Or pulsar proper motion/ram pressure?
Confirmation of the crushed PWN scenario …

... in the HESS J1825-137 / G 18.0-0.7 system


pulsar proper motion (VLA) perpendicular to relic PWN direction
If INTEGRAL source can be identified with X-ray (synchrotron) nebula
→ Object is a “Pevatron”
Chandra:
- Compact source: identified as pulsar
- PWN dominates up to $\sim 10$ keV

HESS J1813-178: Identification with X-ray PWN?

INTEGRAL pulsars with known $E_{\dot{\nu}}$

Dean & Hill (astro-ph/0804.3420, RN):

→ Extreme pulsar properties
- Either underluminous in INTEGRAL band ($\varepsilon=0.01$)
- Or spin-down age decoupled from SNR age (cf. e.g. G11.2-0.3)
HESS J1809-193: two PSR counterparts

Dean et al., MNRAS 384, 2008

+ Chandra reanalysis of G11.2-0.3

50% of the 20-100 keV flux from PSR J1811-1925 is from the PWN
But no evidence for a morphological connection to the VHE source
The PWN around PSR J1809-1917


→ The PWN around PSR J1809-1917 is very likely contributing to HESS J1809-193

→ Especially in this case, multiple components in the VHE source cannot be excluded

HESS coll., Komin et al., astro-ph/0709.2432
VHE PWN candidates

- Classification because of association with powerful pulsar
- no X-ray PWN required for this classification
- Large ε-values are in principle possible (decoupling from Edot)

<table>
<thead>
<tr>
<th>VHE source</th>
<th>$F_{0.3-30}$ *</th>
<th>PSR name</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESS J1616–508</td>
<td>$3.7 \times 10^{-11}$</td>
<td>J1617–5055</td>
<td>1%</td>
</tr>
<tr>
<td>HESS J1804–216</td>
<td>$2.9 \times 10^{-11}$</td>
<td>B1800–21</td>
<td>2%</td>
</tr>
<tr>
<td>HESS J1809–193</td>
<td>$2.8 \times 10^{-11}$</td>
<td>J1809–1917</td>
<td>2%</td>
</tr>
<tr>
<td>HESS J1912+101</td>
<td>$1.8 \times 10^{-11}$</td>
<td>J1913+1011</td>
<td>2%</td>
</tr>
<tr>
<td>HESS J1718–385</td>
<td>$4.3 \times 10^{-12}$</td>
<td>J1718–3825</td>
<td>0.5%</td>
</tr>
<tr>
<td>HESS J1303–631</td>
<td>$2.3 \times 10^{-11}$</td>
<td>J1301–6305</td>
<td>7%</td>
</tr>
<tr>
<td>HESS J1702–420</td>
<td>$1.4 \times 10^{-11}$</td>
<td>J1702–4128</td>
<td>11%</td>
</tr>
</tbody>
</table>

* in units of erg cm$^{-2}$ s$^{-1}$

HESS coll., Gallant et al., AIP 978, 2008
HESS J1718-385: a VHE PWN candidate

XMM, 0.5-10 keV

XMM, point sources subtracted

compact but still extended X-ray emission around PSR J1718-3825
→ likely the compact X-ray PWN, but no clear link to the HESS source

+ Suzaku pointing to search for weak diffuse emission

Hinton et al., A&A 476, 2007
HESS J1718-385: a VHE PWN candidate

Suzaku, 0.5-7 keV

GP et al. 2007 (Suzaku conf.):
diffuse emission could morphologically connect XMM PWN with HESS source
HESS J1718-385: a VHE PWN candidate

“Underluminous” PWN

PSR J1838-0655 (X-ray pulsar discovered using XTE)
Gotthelf & Halpern, astro-ph/0803.1361

Detection of PWN around PSR J1617-505 with Chandra, but association with HESS J1616-508 inconclusive
Kargaltsev et al., astro-ph/0805.1041

Chandra PWN review, Kargaltsev & Pavlov, astro-ph/0801.2602
HESS J1837-069: Chandra + RXTE

- White contours: VLA 90 cm
- Yellow contours: HESS
- Map: Chandra ACIS 2-8 keV

\[
\text{PSR J1838-0655}
\]

Gotthelf & Halpern,
astro-ph/0803.1361

- \( \text{Edot} = 5.5 \times 10^{36} \text{ erg s}^{-1} \)
- \( \eta_{\text{PWN, X}} = 10^{-3} \)
- age = 23 kyr

→ Good counterpart to HESS source
→ But some interesting / open issues
AX J1838.0-0655: Compact source dominates

INTEGRAL source (Malizia et al. 2006, Lutovinov et al. 2005):
Possible hard X-ray – VHE connection

\[ \text{INTEGRAL source is presumably not the extended PWN (cf. HESS J1813-178)} \]
Reflexion halo around AX J1838.0-0655?

Predehl & Schmitt 1995 (ROSAT)

$N_H \sim 5 \times 10^{22} \text{ cm}^{-2}$
$\rightarrow \tau_{\text{sca}} (1\text{keV}) = 2.5 !!!$

AX J1838.0-0655:

Open circles: additional intrinsic absorption

Cf. G21.5-0.9, Bocchino et al. 2005
Summary

• VHE astronomy provides a new window to PWN physics
• Efficient way to detect (relic) PWN because of the ubiquitous target photon fields for IC (CMB, + dust and starlight), independent of B-field
• Combination of X-ray and VHE allows e.g. determination of B-field (with caveats)
• Currently, for identification of VHE PWN mostly morphological arguments and efficiency into VHE flux is used
• X-rays reflect mostly current spin-down power (short synchrotron lifetime), whereas VHE, similar to radio, should allow to access the entire deposited pulsar energy budget (for moderately low B-fields)
• Cf., e.g., to $R_{PWN} / R_{\text{shock}}$ – “radius method” by Swaluw & Wu (ApJ 555, 2001) based on radio-PWN to infer the initial spin rates
At the sensitivity limit of current VHE instruments

H.E.S.S. (adaptively smoothed)

Two shell-type supernova remnants
Plausible hadronic emission scenarios exist for both sources

HESS source of the month April 2008

At the sensitivity limit of current VHE instruments

H.E.S.S. (adaptively smoothed)

→ Nonthermal X-ray sources hinting at pulsars / PWN

HESS source of the month April 2008

Chandra

HESS collaboration,
CTA: The Cherenkov Telescope Array
CTA (Cherenkov Telescope Array): target sensitivity

Taken from ASPERA roadmap
CTA: possible array layout

Option:
Mix of telescope types

Not to scale!
Consortium is currently being formed
Mostly European, recent statement for Japanese commitment
Currently under design study
“Call for proposals” for science requirements
CTA: The Cherenkov Telescope Array

http://www.cta-observatory.org