Study of Galactic Sources with H.E.S.S.

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Overview

- **Our favorites:** Supernova remnants
  - Shell type SNR
  - Pulsar wind nebulae: VHE Plerions
- **Newcomers and old friends:** Binary systems
- **Enigmatic:** Unidentified sources
Shell-type SNR: “Vela Jr”

- RX J0852.0-4622:
  - X-ray detected non-thermal SNR hidden by Vela SNR (ROSAT Aschenbach, Nature 1998)
  - 2° diameter
  - X-ray & radio spectrum (faint) difficult to disentangle from Vela SNR
  - Distance & age uncertain - reasonable range 0.2 (44Ti) to 1 kpc (column density), thin filaments, X-ray spectra -> 0.2-0.5 kpc, <1-2 kpc (closer than Vela ridge) see eg Iyudin et al. 2005, Slane et al. 2001, Bamba et al. 2005)
  - Possibly result of core collaps SN - central compact object associated with NS
  - CANGAROO detected TeV excess (Katagiri et al. 2005)
  - H.E.S.S. detection based on 4.7 hrs of data - rainy season (Aharonian et al. 2004)
Morphology Vela “Jr”

- Large extension: Challenging background subtraction - different methods employed - see e.g. Lemoine-Goumard et al. 2005, 2006
- Total excess of 5200 events (19σ)
- Thin shell: (18.3±2.2)% (0.95 c.l.)


20 hrs on-source data with 4 telescopes (Dec'04-May'05), shifted pointing pattern

28-31 August 2006, Madison Wisconsin
No strong spectral changes: Similar morphology for two energy bands

Fit a spatially averaged energy spectrum
Energy spectrum: 0.3-20 TeV

- Power law:
  - Spectral index
    \[ 2.24 \pm 0.05 \text{stat} \pm 0.15 \text{sys} \]
  - Integral flux \( (10^{-12} \text{cm}^{-2} \text{s}^{-1}) \):
    \[ I(E>1\text{ TeV}) = 15.2 \pm 0.7 \text{sys} \pm 3.2 \]
- But: Indications for a cut-off
- Cross-checked with different background estimates & spectral reconstruction techniques (e.g. forward folding)
- Confirms previous result
The multiwavelength picture: Correlation of VHE & X-ray images

- X-ray and VHE features correlate
  - NW rim
  - SE rim
- Some deviations:
  - NE rim
  - W rim
Correlation with X-rays: 70%
Correlation with gas density? Not at all

No correlation with CO for varying $v$ (distance)
Electronic scenario at 0.2 kpc

- Time-dependent model with free injection spectrum for two different distances, $W_{\text{inj}} = 10^{50}$ erg

- Low density environment (0.1 cm$^{-3}$)
- Small magnetic field (6 μG)
- $t(200\text{pc}) = 500$ yrs
- Injection with 2.4, $E < 40$ TeV
- $\Delta r_{\text{shell}} (200\text{pc}) < 0.78 \text{pc}$
- $T_{\text{esc}} (40 \text{ TeV}) \sim 300$ yrs < age
- Particles should have escaped > thicker shell
- This scenario appears inconsistent
- Overpredicts radio data (lower energy cut-off?)

D=0.2 kpc

Blue: hadronic (pp)  
red: electronic (Sy)  
dashed: IC  
dot-dashed: Bremsstrahlung
Electronic scenario at 1 kpc

- Very similar to the nearby case, requires higher energy cutoff (100 TeV) - cooling for age=9000 yrs
- No problem with escape time etc
- Consistent picture
Hadronic scenario

- SNR distance < 600 pc not too exceed energetics
  - Ambient medium density < $2.9 \times 10^{-2} \left(D/1\text{kpc}\right)^{-0.5} f^{-0.5}$ cm$^{-3}$ (emission measure) for hot (>keV) phase
  - $W_p (1 \text{ GeV-100 TeV}) \sim 10^{49}$ erg $\left(D/200 \text{ pc}\right)^2 (n/1 \text{ cm}^{-3})$

- Chandra filaments (d=0.24 (D/kpc) pc): High downstream magnetic field 300-500 μG-Cosmic ray modified shock

- Electrons and Hadrons are injected with the same spectra - could in principle be different to avoid trouble to fit X-ray data
Hadronic case: Two distances

- Power law $2.1 \ E < 110 \ TeV$
- $B=120 \ \mu G, \ n=0.2 \ \text{cm}^{-3}$
- Predicted X-ray spectrum too hard

- Power law $2.0 \ E < 110 \ TeV$
- $B=85 \ \mu G, \ n > 2 \ \text{cm}^{-3}$ Bubble?
- Predicted X-ray spectrum too hard
- Magnetic field too low with respect to Filaments?
SNR: The case of RX J1713.7-3946

- RX J1713.7-3946:
  - X-ray detected SNR (ROSAT All-sky survey Pfeffermann & Aschenbach 1996)
  - 1° diameter, possibly interacting with molecular cloud at D=1 kpc
  - non-thermal X-rays dominate (Koyama et al. 1997, see also Cassam-Chenaï et al. 2004)
  - Distance uncertain - latest “guess” 1 kpc (column density) - consistent with historical SN393
  - CANGAROO detected TeV excess (Enomoto et al. 2002)
RX J1713.7-3946

- 7700 excess events (39σ)
- “Thick shell”, ΔR~55%R

Spatially resolved spectra

- No significant spatial variation of spectra at VHE energies
- Significant spectral softening to the SW, center at X-ray energies
- Derive a spatially averaged energy spectrum

Cassim-Chenaï et al. (2004)
Energy spectrum: 0.2-40 TeV

- Spectrum 2003&2004 compatible
- Within systematics compatible with CANGAROO
- Power law
  - Index $2.26 \pm 0.02_{\text{stat}} \pm 0.15_{\text{sys}}$ (poor fit)
  - $I(>1 \text{ TeV}) = 13.5 \pm 0.4 \times 10^{-12} \text{ cgs}$
- Exponential cut-off reasonable fit
  - Index $1.98 \pm 0.05$
  - $E_c = (12 \pm 2) \text{ TeV}$
MWL morphology: VHE vs. X-rays

- Remarkably good match! (80% correlation)

Color-scale: ASCA GIS 1-5 keV smoothed
Contours: HESS excess map
MWL morphology: ISM density from CO (at 1 kpc)

- Some agreement evident
- Slightly shifted in azimuth
- Larger dynamics in the CO w.r.t. HESS
Electronic scenario: RX J1713.7-3946 - uncomfortably low B-field.

D = 1 kpc
age = 1000 yrs
n = 1 cm\(^{-3}\)

Injection of electrons, p = 2,
E < 100 TeV
Total energy: \(O(10^{37} \text{ erg})\)

See also Porter et al. (2006) – slightly higher B field possible taking higher \(u_{\text{seed}}\) for IC

High \(E_{\text{max}}\) with small B?

More complicated scenarios...
Hadronic origin

D=1 kpc  
age=1000 yrs  
n=1.5 cm$^{-3}$ (0.02..2)  
B=35 $\mu$G

Spectrum with Index 2, 120 TeV cut-off  
$W_p (2-400 \text{ TeV})=6 \times 10^{49} \text{ erg} \ (D/1 \text{ kpc})^2 \ (n_1)^{-1}$  
$W_p (0.001-400 \text{ TeV}) \sim 10^{50} \text{ erg}$

Perfect fit to the data

Energetics ok (10% of total SNR energy in CR)

Very good fit to MWL data
Direct comparison

- Similar flux, spectrum ($E_{\text{max}} \sim 100$ TeV $\ll E_{\text{knee}}$)
- Different morphology
- IC fits - low magnetic field, Hadronic origin better
..for completeness

- 231 gal SNR known (Green et al. 2001)
- O(10) with non-thermal X-rays
- At least 3 detected as TeV sources
Pulsar wind nebulae

- “Classical” Object: The Crab nebula (SN1054)
  - Young, powerful pulsar
  - Standard candle
  - ...still with some surprises

DH et al. (2005)
H.E.S.S. observations indicate spectral softening

Exponential cut-off at 15 TeV

Awaiting more data

Explanations:
- Systematic error
- Fluctuations
- or... Physics (time variability as seen in hard X-rays)

astro-ph/0607333, accepted for publication in A&A
The offset PWN: G18.0-0.7 (HESS J1825-137)

• Middle aged (21 kyrs) pulsar at 4kpc PSR J1826-1334 powers asymmetric X-ray Synchrotron nebula (arc min size)

• Surprisingly: Gamma-ray emission from larger (1°) size and displaced region with asymmetric morphology

• Quite high VHE lum>10^{35} erg/s
Explanation

- Pulsar wind nebula modified by reverse shock of (undetected) shell: “crushed PWN”
- Close environment: Electrons cool via synchrotron ($t_{\text{cool}} < t_{\text{PWN}}$) emitting X-rays
- Cooled electrons fill larger volume, emitting IC VHE gamma-rays on CMB+IR+Stellar light
- Relic nebula traces the evolution of the PWN, spectral evolution with distance
- $W_e \approx 10 \times E_{\text{dot}} \times t_{\text{PWN}} \rightarrow$ Higher spin-down in the past
Spatial variation of the TeV spectrum!

- First time detection of spatially resolved spectral changes
- Possible indication for cooling of electrons -> consistent with offset nebula picture
Another offset Nebula? Vela X

- Middle aged Vela PSR&PWN at 290 pc
- Similar shifted/asymmetric PWN(?): Vela X
- VHE signal from Vela X
- BUT: X-rays/VHE morphology&size similar (not like G18.0-0.7)
- Inverse Compton scenario (efficiency<0.1%), but alternative: Nucleonic origin (dh et al. 2006) -> Neutrino source!
A young pulsar/PWN system: MSH 15-52

- PSRB1509: $E_{\dot{\text{m}}} = 1.8 \times 10^{37}$ erg/s, 1.55 kyrs
- Distance 4.2 kpc
- Extended X-ray nebula
- VHE source correlates with non-thermal X-ray nebula
- Extended INTEGRAL source (non-diffusive transport?)
- No spatial variation of VHE/X-ray spectra

HESS spectrum: pure power-law up to 40 TeV

Chandra, Gaensler et al. 2002
The wings of Kookaburra

- PSR J1420-6048: Middle aged pulsar (13 kyrs) at 5.3 kpc with compact X-ray nebula K3
- Association with EGRET source 3EGJ1420-6038?

- Rabbit: PWN candidate (no pulsar known)
- VHE plerion similar to NE wing
Candidates to the VHE Plerion zoo

- PSR B1800-21:
  - $D = 3.9$ kpc
  - Required efficiency: 2.4%

- PSR J1702-4128
  - $D = 4.8$ kpc
  - Required efficiency: 11%

- PSR J1617-5055:
  - $D = 6.8$ kpc
  - Required efficiency: 1.3%
  - See also Matsumoto et al. (2006)
  - $F_x < 3.1 \times 10^{-13}$ cgs = $F_{VHE} / 60$

A systematic search in the galactic plane scan for HESS source candidates assoc. with large $E_{\text{dot}}/D^2$ PSR: (Carrigan et al. 2006): two more candidates

- HESS J1809-193, HESS J1718-384

28-31 August 2006, Madison Wisconsin
**Composite PWNe/SNRs**

- G0.9+0.1: VHE emission from plerionic part (no pulsar detected)
- HESS J1634-472: maybe associated with Crab like pulsar/SNR G337.2+0.1 at d=14 kpc (Combi et al. 2005)
- HESS J1813-178: New (unpublished XMM-Newton) observation reveal X-ray plerion making this a composite PWN/SNR
- HESS J1834-087 associated with G23.3-0.3 (W41): VHE emission from central region
Gamma-rays from binary systems: LS 5039 & PSR B1259-630/SS2883

F. Mirabel (2006)
• Discovery & Light curve during periastron passage in March 2004
• Next peri-astron in summer 2007 (not visible)
• Ongoing observations try to establish the quiescent flux
• Ideal laboratory for PWN/stellar outflow interactions (IC vs. pp) see also Kirk et al. (2005), Chernyakova et al. (2006), Khangulyan et al. (2006), Dubus (2006)
Flux variability from LS 5039

- Deep observations (2004+2005): 70 hrs, 2000 $\gamma$, 40$\sigma$
  - Light curve

Clearly a variable source!
Orbital modulation from LS 5039

- Deep observations: 70 hrs, 2000 γ, 40σ
  - Search for periodicity (Lomb-Scargle), post-trial chance probability <10^{-15}, P=3.9078d±2.1min

Science 309, 746 (2005)
Non-periodic variability?

- After subtracting the periodic variability - $3\sigma$ evidence for variability
Orbit

Folded light curve

- Maximum coinciding with inferior conjunction
- Minimum around superior conjunction (non-vanishing!)
- Sufficient statistics to perform phase-resolved spectroscopy

Dieter Horns - University of Tübingen
Phase resolved spectroscopy: 2 intervals

- No orbital modulation at 200 GeV
- Max modulation at several TeV
- SUPC: $\Gamma=2.53\pm0.07$
- INFC: $\Gamma=1.85\pm0.06$ with $E_c=(8.7\pm2)$ TeV
Phase resolved spectroscopy:

- With one exception: Flux-Photon index are correlated
- Similar to X-rays flux vs hardness (Bosch-Ramon et al. 2005 - note, no X-ray orbital modulation found)
Strictly simultaneous MWL data with Chandra

- Very high VHE state & hard spectrum (no cut-off!)
- Simultaneous Chandra data: High and very hard
- More data desirable at this phase interval
Origin of orbital modulation

- Variation in accretion (e.g. Paredes et al. 2006)
- Absorption (e.g. Dubus 2006, Böttcher & Dermer 2006)
  - Inavoidable (Neutrino-flux could be high, Aharonian et al. 2006)
  - Consistent light curve (+cascading)
  - Spectral variations are not consistent
- Production (varying $E_{\text{max}}$, IC/KN cooling)
  - Should correlate with Apastron/Periastron -phase shift due to cascading?

Personal guess: A mixture of these effects
Unidentified sources

- Result of Galactic plane scan:
  - 12 sources with counterparts (different quality of association - see e.g. Funk (2006))
  - 3 sources without plausible counterparts
    - HESS J1303-631 (Chandra 55 ks, XMM-Newton 60 ks)
    - HESS J1614-518 (Swift 2 ks, deeper XMM-Newton to come)
    - HESS J1708-410 (new XMM-Newton data to come!)
  - Case-by-case effort to nail-down counterparts with X-ray and radio observations
HESS J1614-518

- Two faint X-ray counterparts (Landi et al. 2006) at the energy flux level of $5 \times 10^{-13}$ cgs

Object 1:
unidentified X-ray source with optical counterpart

Object 2:
unidentified X-ray source with nearby extended radio counterpart
PMN 1613-5143

We have just taken XMM-Newton data

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Fig. 1.— XRT 0.3–10 keV image of the region surrounding HESS J1614-518. The ellipse represents the extension of the TeV source, while X-ray sources are labelled as in Table 2.
Instead of a summary: An outlook

- HESS takes >200 hrs of data from the Galactic plane/year: Many more sources will appear (standard candle: $N(>S) \sim t^{0.75}$)

- With GLAST, H.E.S.S. II: Energy coverage $0.1-10^4$ GeV!

- Neutrino telescope: Identify emission mechanism

- With MWL observations (X-ray, Radio, & optical): Identify the source

- Item for the wishlist: 10-100 TeV, $A=10 \text{ km}^2$ detector