H.E.S.S. Observations of the LMC

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What is the Large Magellanic Cloud?

- a satellite galaxy of the Milky Way
- \( \sim 10^\circ \) diameter (20x full moon)
- extension: 8 kpc
- distance: 50 kpc
- inclination: 31°
High Energy Stereoscopic System

- 5 Imaging Cherenkov Telescopes
  - record Cherenkov light of air showers
- 5° field of view (CT 1–4)
- 100 GeV ... tens of TeV
- Namibia → only instrument for TeV observations of the LMC
- data presented here: H.E.S.S. phase I → only 4 telescopes
H.E.S.S. LMC Observation Campaign

- time line:
  - 2004: start with SN 1987A
  - 2009: 49 h (published 2012)
  - 2013: 210 h (this talk)

- observation conditions
  - large zenith angle (45° - 52°)
  - → energy threshold ~700 GeV

- spatial coverage:
  - roughly: 2° around N 157B
    - contour line: 2° mean camera offset
  - main targets: N 157B, SN 1987A (Tarantula nebula)
  - secondary target: N 132D
The Pulsar Wind Nebula N 157B Revisited

- 613 gamma rays, 33 σ
- confirms previous result [H.E.S.S. A&A 545, L2 (2012)]

- spectral index $2.8 \pm 0.1$
- no significant spectral cut-off
- $L_{1-10 \text{ TeV}}(50 \text{ kpc}) = (6.8 \pm 0.3) \times 10^{35} \text{ erg/s}$
- under-estimation of flux in 2012:
  - imperfect modelling of instrument response
The Pulsar Wind Nebula N 157B Revisited

- pulsar wind nebula powered by PSR J0537–6910 ($\dot{E} = 4.9 \times 10^{38} \text{ erg/s}$)
- inverse Compton emission on strong infra-red fields $\rightarrow$ bright in gamma rays
- X-ray synchrotron emission $\rightarrow$ low magnetic field of 45 $\mu$G
- constant injection of 11% $\dot{E}$ into electrons $>$400 GeV
- Milky Way counterpart:
  - Crab Nebula
    - $\dot{E} = 4.5 \times 10^{38} \text{ erg/s}$
    - same model
      - 123 $\mu$G
      - 50% $\dot{E}$
  - $\rightarrow$ N 157B apparently inefficient accelerator
- new Fermi results: 2\textsuperscript{nd} component?
New Source Discovery

- additional emission SW of PWN
  - 130 pc at 50 kpc
- >5σ above spill-over
- two-source morphology favoured by 8.8σ
- position (contours) compatible with
  - shell of superbubble 30 Dor C
  - star clusters of LH 90
- not compatible with SN 1987A
- note: angular resolution does not allow conclusion on morphology
The Superbubble 30 Dor C

- non-thermal X-rays from shell
- $\rightarrow$ TeV emission from shell likely
- alternative scenarios
  - SNR
  - unseen pulsars/PWN
  - background AGN

- spectral index $2.6 \pm 0.2$
- $L_{1-10\text{ TeV}}(50 \text{kpc}) = (9 \pm 2) \times 10^{34} \text{ erg/s}$
  - corrected for N 157B spill-over
The Superbubble 30 Dor C
The Superbubble 30 Dor C

- **hadronic scenario**
  - energy in protons
    \[ W_{pp} = (0.7 - 25) \times 10^{52} \left( \frac{n_H}{1 \text{ cm}^{-3}} \right)^{-1} \text{ erg} \]
  - even for 5 supernova explosions
    high density needed: \( n_H > 20 \text{ cm}^{-3} \)
    - thermal X-rays
      indicate low density:
      \( n_H \approx 0.4 \text{ cm}^{-3} \)
      [Bamba et al. 2004]

- **leptonic scenario**
  - low magnetic field:
    \( \sim 15 \mu\text{G} \)
  - \( 4 \times 10^{48} \text{ erg in electrons} \)
The Superbubble 30 Dor C

- hadronic or leptonic: no model favoured
- but: evidence for efficient particle acceleration in a superbubble
- first unambiguous detection of a superbubble in gamma rays
- Galactic counterpart: Westerlund 1
  - emission from PWN?
The Supernova Remnant of SN 1987A

- **not detected**
- gamma ray flux $F (>1 \text{ TeV}) < 5 \times 10^{-14} \text{ cm}^{-2}\text{s}^{-1}$
  - 99% confidence level
- gamma ray luminosity $L (>1 \text{ TeV}) < 2.2 \times 10^{34} \text{ erg/s}$
- **hadronic scenario**
  - predicted
    Berezhko, Ksenofontov & Völk 2015
  - shock front has reached equatorial ring with $n_H = 10^3 \ldots 3 \times 10^4 \text{ cm}^{-3}$
  - $f$ is fraction of particles interacting with the ring: $f \sim 0.2$
  - energy in protons: $W_p < 1.4 f \times 10^{48} \text{ erg}$
    → **SN 1987A not enough time for acceleration**
H.E.S.S. LMC Observation Campaign

optical, 576 – 788 nm (false colour image)

[A. Mellinger, PASP 121, 1180 (2009).]
The Supernova Remnant N 132D

- potential gamma ray emitter [Katz & Waxman, 2008]
- evidence for emission:
  - $4.7\,\sigma$ at nominal test position
  - *Fermi* detection at MeV/GeV

- spectral index $2.4 \pm 0.3$
- $L_{1-10\,\text{TeV}}(50\,\text{kpc}) = (9 \pm 2) \times 10^{34}\,\text{erg/s}$
The Supernova Remnant N 132D

- X-ray features
  - strong thermal emission
  - upper limit on non-thermal emission
  - high explosion energy $6 \times 10^{51}$ erg
  - pre-shock density $2.6 \, \text{cm}^{-3}$
  - age 6000 years
  - [Hughes et al. 1998]
The Supernova Remnant N 132D

**hadronic scenario**
- energy in protons
  \[ W_{pp} = 10^{52} \left( \frac{n_H}{1 \text{ cm}^{-3}} \right)^{-1} \text{ erg} \]
- \( \rightarrow \) efficient accelerator (17% to CR) or high post-shock density
- possible interaction with interstellar clouds

**leptonic scenario**
- infra-red from dust
- magnetic field \( \sim 20 \mu \text{G} \)
- depends on level of non-thermal X-rays
- new Fermi results: hadronic/leptonic?
- N 132D intermediate age
  - how long do SNRs accelerate up to \( 10^{15} \text{ eV} \)
Fermi sources not detected with H.E.S.S.

- PSR J0540–6919: 1st extra-galactic $\gamma$-ray pulsar
  - *Fermi* detects pulsed emission
  - X-ray luminous PWN
  - not detected with H.E.S.S.
    - $F(>1\text{TeV}) < 4.8 \times 10^{-14} \text{ cm}^{-2}\text{s}^{-1}$

- Unassociated source “P3”
  - HII region NGC 2029 / NGC 2032
  - marginally consistent with
    - SNR DEM L241
    - Seyfert 1 galaxy 2E 1445
  - steep spectrum
  - not observed with H.E.S.S.
Summary

- **deep H.E.S.S. observations → 3 TeV sources in LMC:**
  - PWN N 157B
    - Crab counter-part
    - but low magnetic field and efficiency
  - 30 Dor C
    - first unambiguous detection of a superbubble in gamma rays
  - N 132D
    - one of the oldest TeV emitting SNRs
  - first individual cosmic-ray sources in an external galaxy
- **tip of the iceberg?**
  - future observations with CTA