Extreme Galactic Particle Accelerators

The case of HESS J1640-465

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High-energy particles in space

- Why are they important?
  - energy density of is comparable to star light, CMB, and interstellar B-fields
  - impact on star-formation process (chemistry in dense molecular clouds)
  - source of ionisation in the Galaxy
  - form significant contribution to the pressure in many astrophysical sources (e.g. SNRs, AGN)

- Properties of cosmic rays
  - spectrum follows a power law in energy
  - >10 decades in energy, >30 decades in flux
  - produced by acceleration of particles
  - SNR shells likely acceleration site of CRs up to the “knee” (∼3 x 10^{15} eV!)

How can we find the accelerators?

→ Neutral messenger particles (photons and neutrinos)
Non-Thermal Radiation

• Tracers for ultra-relativistic electrons and hadrons

adapted from W. Hofmann
Non-Thermal ‘Windows’

- Tracers for ultra-relativistic electrons and hadrons
- Non-thermal windows
  - radio
  - hard X-rays
  - γ rays

- Synchrotron Emission
  - Optical, UV, Soft X-ray – Heavily absorbed

- Inverse Compton Scattering
  - π⁰ decay

Energy Flux (νF_ν)

adapted from W. Hofmann
The H.E.S.S. telescope array

Key Parameters
- 5 imaging atmospheric Cherenkov telescopes located in Namibia
- Energy range: $\sim 100$ GeV - $\sim 50$ TeV
- Angular resolution: $\sim 0.1^\circ$
- Energy Resolution: $\sim 15\%$
- Field-of-View: 5º

Success of H.E.S.S.
- Stereoscopic approach ($\gamma$/hadron separation, sensitivity, energy resolution, ...)
- Southern hemisphere location (see inner Galaxy)

Galactic VHE $\gamma$-ray sources
- cluster tightly along the Galactic plane
- Trace molecular gas and regions of massive star formation
- Many sources coincident with objects at late evolutionary stages:
  $\rightarrow$ Pulsar Wind Nebulae (1/4)
  $\rightarrow$ Shell-type SNRs or SNR – MC interaction regions (1/5)
  $\rightarrow$ $\gamma$-ray binaries, stellar cluster
The H.E.S.S. telescope array

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see Richards plenary talk for more info on Cherenkov telescopes and the next generation CTA

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HESS J1640-465

**HESS source**
- discovered in Galactic Plane Scan (2005)
- rather compact, strong $\gamma$-ray emitter
- coincident with SNR G338.3-0.0

**Environment**
- in a very complex region (e.g. HII region and stellar cluster nearby)
- not much known about the SNR (incomplete shell, 8' size, no spectral measurement)
- HI and X-ray absorption measurements suggest large distance of $\sim 10$ kpc
Association / X-rays

- **Swift (Landi et al. 2006)**
  - found point-like source

- **XMM (Funk et al. 2007)**
  - nothing spectacular in the low energy map
  - 2 keV – 10 keV maps shows significantly extended source

- **Chandra (Lemiere et al. 2009)**
  - detect point-like object (PSR) and confirm extended PWN candidate
  - also other characteristics point towards PWN origin

→ suggests central source is of non-thermal nature (PSR) and powers synchrotron nebula
Association / GeV γ-rays

- Slane et al. (2010)
  - 15 months of data acquired with Fermi satellite
  - position consistent with HESS
  - no extension detected
  - reconstructed spectrum between 200 MeV – 50 GeV
  - connects with TeV spectrum
  - Also interpreted in PWN scenario
HESS J1640-465 today

Data & Analysis
- much more data (14 → 83 hr)
- improved analysis techniques
- γ-ray excess: 330 → 1850

Position & Extension
- significantly extended emission: $\sigma_{\text{Gauss}} = 4.3' \pm 0.3'$
- extended towards HII region
- suggestive of asymmetry along northern SNR shell (2σ effect)
- within HESS extension PWN and northern SNR shell

Preliminary
HESS J1640-465 today

**Spectrum**
- nicely connects with Fermi spectrum at lower energies
- fit of exponential cut-off power law gives to TeV:
  - $\Gamma = 2.15 \pm 0.1$
  - $E_c = (7.3 \pm 2.0) \text{ TeV}$
- pure power law cannot be ruled out (1% probability)
- spectral points up to 10 TeV

**What is the source of the TeV $\gamma$-ray emission?**
- SNR or PWN?
- investigate spectral and morphological characteristics
What is the source of γ-rays?

- **Pulsar Wind Nebula**
  - quite common source of very-high-energy γ-rays
  - spatial coincidence of GeV and TeV source with PWN candidate in X-rays

What you would expect:

- Inverse Compton + synchrotron emission
- peak between Fermi and HESS range
- very hard Fermi spectrum

![SED of HESS J1825-134](image)
PWN scenario

Pros
- quite common source of very-high-energy $\gamma$-rays
- spatial coincidence of GeV and TeV source with PWN candidate in X-rays, but...

Cons
- smooth $\gamma$-ray spectrum (not seen in any other PWN)
- TeV source more extended than SNR (not seen in any other PWN)
- no radio emission seen from PWN, upper limit factor $\sim 5$ below models
  $\rightarrow$ GeV very hard to explain as from PWN
  $\rightarrow$ fine-tuning required to match GeV and TeV

Spectrum looks like other prominent GeV and TeV-detected SNRs
SNR scenario

**Pro SNR**

- New radio measurements (Castelletti et al., 2011) show non-thermal radio emission from shell
- Re-analysis of XMM data didn’t show non-thermal X-ray emission from shell
- Fermi-LAT position and HESS extension compatible with protons interacting with gaseous material that produce γ-rays
- Simple model can explain the SED without any fine-tuning:
  - $B = 25\mu G$, $E_{c,e} = 10$ TeV,
  - $\Gamma_e = 2.0$, e/p ratio of 1/100
- Inverse Compton emission orders of magnitude below measurements
  - $E_{c,p} = 50$ TeV, $\Gamma_p = 2.2$,
  - $n_H = 150$ cm$^{-3}$
  - $W_p = 2.5 \times 10^{50}$ erg
HESS J1640-465 an extreme accelerator

Implications

- Product of energy in protons and target density of $4 \times 10^{52}$ erg cm$^{-3}$ is required to explain observed luminosity
- Need high densities to reduce energy in relativistic protons (could be up to 350 cm$^{-3}$)
- Such dense gas has not been found yet
HESS J1640-465 an extreme accelerator

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Why is that extreme?
- Canonical SN has $E_{\text{kin}} = 10^{51}$ erg, and $E_{\text{kin}} \rightarrow E_{\text{CR}} = 10\%$.
- These particles interact and produce $\gamma$-rays.
- For density of $\sim 100$ cm$^{-3}$ and canonical 10% in CRs:
  - $E_{\text{SN}}$ could be $\sim 4 \times 10^{51}$ erg.
  - Acceleration efficiency could be up to 40%.

Extreme implies
- Very efficient accelerator and/or very energetic supernova.
- Potentially higher, as only part of SN shell interacts with dense material.
- Brightest SN in TeV $\gamma$-rays (factor 10), as bright as other SNe in GeV $\gamma$-rays.
The future

- **HESS J1640-465**
  - Need better PSF and sensitivity to disentangle PWN from SNR shell and maybe even resolve the shell
  - Need spectral coverage to detect photons of 100 TeV energies (→Pevatrons)

- **How to do that?**
  - HESS 2 (600 m² telescope) will deliver some of that
  - CTA will be the next big thing → see Richard’s talk after the coffee break!