Very high energy emission from the hard spectrum sources HESS J1641–463, HESS J1741–302 and HESS J1826–130

Ekrem Oğuzhan Angüner, Sabrina Casanova, Igor Oya, Felix Aharonian, Alexander Ziegler and Pol Bordas for the H.E.S.S. Collaboration
Outline

• The High Energy Stereoscopic System
• Origin of Cosmic Rays
• Galactic Center as a PeVatron
• Hard Spectrum H.E.S.S. Sources
• Hadronic & Leptonic Scenarios
• Conclusions
The High Energy Stereoscopic system

- H.E.S.S. is a system of Imaging Atmospheric Cherenkov Telescopes that investigates cosmic $\gamma$-rays in the energy range from 10's of GeV to 10's of TeV.

**H.E.S.S. Phase I (2004)**
- Four 12 m Cherenkov telescopes, FoV 5°
- Energy threshold 100 GeV
- Angular resolution < 0.1°

**H.E.S.S. Phase II (2012)**
- + One 28 m Cherenkov telescope (CT5), FoV 3.5°
- Energy threshold ~20 GeV
- Angular resolution 0.1° to 0.4°

- The data presented in this study were taken with H.E.S.S. phase I array configuration (does not include any CT5 data).

E. O. Angüner, ICRC 2017, 2017/07/17, Busan, Korea
Origin of Cosmic Rays

- The CR spectrum shows two distinct features “the knee” and “the ankle”.

CRs up to the knee $\rightarrow$ Galactic (accelerated in galactic objects like SNRs).

CRs between the knee and the ankle $\rightarrow$ Unclear (thought to be Galactic but the energies are too high for being produced in the SNR shocks)

CRs beyond the ankle $\rightarrow$ extra-Galactic.

- Local flux of CRs gives a correct approximation for the level of Galactic CRs, but can be significantly different in the vicinity of CR accelerators.

- Neutral messengers (photons & neutrinos) can be used for tracing back to the origin of their astrophysical sources.

- The origin of cosmic-rays is a 100-year-old mystery.

\[ J_{\text{CR}}^{(p)} = 1.8 \times E_{\text{GeV}}^{-2.7} \text{ GeV}^{-1}\text{s}^{-1}\text{sr}^{-1}\text{cm}^{-2} \]
Acceleration of PeV protons in the Galactic Centre [1]

- The diffuse emission spectrum extraction region.

- The diffuse emission spectrum is a power-law (pp interactions → subsequent $\pi^0$ decay, reflecting the parent proton spectrum)

$$
\Phi = (1.92 \pm 0.08_{\text{stat}} \pm 0.28_{\text{sys}}) \times 10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}
$$

$$
\Gamma = 2.32 \pm 0.05_{\text{stat}} \pm 0.11_{\text{sys}}
$$

- Recall that the GC source has a cut-off (at 10 TeV) while the diffuse emission has not.

- Assuming a cutoff in the parent proton spectrum → 1σ, 2σ and 3σ cutoff → 2.9 PeV, 0.6 PeV and 0.4 PeV.

- This is the first robust detection of a VHE cosmic hadronic accelerator which operates as a PeVatron.

The GC is not able to sustain the CR population today unless it was more powerful in the past. We might need other PeV accelerators in the Galaxy.

Sources capable of accelerating protons up PeV energies should have relatively hard spectra without showing any cutoff.

We present VHE and MWL data analysis results of three unidentified H.E.S.S. sources show common characteristics:

1-) The astrophysical objects producing such emission must be capable of accelerating the parental particle population up to energies of at least several hundreds of TeV.

2-) They are located near other bright VHE sources, thus their (apparent) emission is contaminated and suffering from source confusion.

3-) Their best fit positions and extensions are spatially coincident with dense gas regions. None of the sources shows variable VHE emission.
H.E.S.S. Data Analysis Results (Morphology)

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Observation Period</th>
<th>Live-time (h)</th>
<th>Significance (σ)</th>
<th>Best Fit Position (J2000)</th>
<th>Extension (°)</th>
<th>Source Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESS J1641−463 (E &gt; 4.0 TeV)</td>
<td>2004 - 2011</td>
<td>72</td>
<td>8.5</td>
<td>R.A.: 16ʰ 41ᵐ 2.1ˢ</td>
<td>0.050</td>
<td>Point-like</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dec.: −46ʰ 18ᵐ 13.0ˢ&quot;</td>
<td>(UL)</td>
<td></td>
</tr>
<tr>
<td>HESS J1741−302 (E &gt; 0.4 TeV)</td>
<td>2004 - 2013</td>
<td>145</td>
<td>7.8</td>
<td>R.A.: 17ʰ 41ᵐ 15.8ˢ</td>
<td>0.077</td>
<td>Point-like</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dec.: −30ʰ 22ᵐ 30.7ˢ&quot;</td>
<td>(UL)</td>
<td></td>
</tr>
<tr>
<td>HESS J1826−130 (E &gt; 0.5 TeV)</td>
<td>2004 - 2015</td>
<td>204</td>
<td>21.0</td>
<td>R.A.: 18ʰ 26ᵐ 0.2ʰ</td>
<td>0.17 ± 0.02</td>
<td>Extended</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dec.: −13ʰ 02ᵐ 1.8ˢ&quot;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

E. O. Angüner, ICRC 2017, 2017/07/17, Busan, Korea

H.E.S.S. Data Analysis Results

HESS J1641–463 (15% > 0.64 TeV)

- Source confusion, especially for the ones located in the vicinity of bright sources.

- Analysis in energy bands is a powerful technique for new discoveries [4]. Contamination decreases with the increasing energy threshold.

HESS J1826–130 (40% > 0.4 TeV)

E. O. Angüner, ICRC 2017, 2017/07/17, Busan, Korea

H.E.S.S. Data Analysis Results (Spectrum)

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Spectral Model</th>
<th>Normalization (at 1 TeV) (10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1})</th>
<th>Index (\pm \text{stat} \pm \text{sys})</th>
<th>Cut-off Energy (TeV)</th>
<th>Flux (&gt; 1 TeV) (Crab Unit %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESS J1641–463</td>
<td>PL</td>
<td>(3.91 \pm 0.69_{\text{stat}} \pm 0.8_{\text{sys}})</td>
<td>(2.07 \pm 0.11_{\text{stat}} \pm 0.2_{\text{sys}})</td>
<td>–</td>
<td>1.8</td>
</tr>
<tr>
<td>HESS J1741–302</td>
<td>PL</td>
<td>(2.1 \pm 0.4_{\text{stat}} \pm 0.4_{\text{sys}})</td>
<td>(2.3 \pm 0.2_{\text{stat}} \pm 0.2_{\text{sys}})</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>HESS J1826–130</td>
<td>ECPL</td>
<td>(8.28 \pm 0.68_{\text{stat}} \pm 1.6_{\text{sys}})</td>
<td>(1.66 \pm 0.11_{\text{stat}} \pm 0.2_{\text{sys}})</td>
<td>(13.5^{+4.7}_{-2.7})</td>
<td>4.0</td>
</tr>
</tbody>
</table>

- Source confusion may potentially distort the observed spectra of VHE \(\gamma\)-ray sources.
Interstellar Medium Study

- Dense gas regions can provide rich target material for accelerated particles to produce VHE emission via pp interactions followed by a subsequent $\pi^0$ decay.

- The distribution of molecular gas is obtained by integrating the $^{12}$CO 1 → 0 rotational line emission measured with the NANTEN Sub-millimeter Observatory.

- **HESS J1641–463 Case:**
  - $n_{\text{Gas}} = \sim 100$ cm$^{-3}$
  - Mass = $2.4 \times 10^5$ M$_{\odot}$
  - Distance = 11 kpc

- **HESS J1741–302 Case:**
  - $n_{\text{Gas}} = 62 – 380$ cm$^{-3}$
  - Mass = $(1.9 – 9.8) \times 10^5$ M$_{\odot}$
  - Distance = 5 – 11.2 kpc

- **HESS J1826–130 Case:**
  - $n_{\text{Gas}} = \sim 600$ cm$^{-3}$
  - Mass = $3.0 \times 10^5$ M$_{\odot}$
  - Distance = 3.7 kpc and 4.7 kpc

---

E. O. Angüner, ICRC 2017, 2017/07/17, Busan, Korea
Hadronic & Leptonic Scenarios

- Assuming hadronic origin and taking into account the properties of the gas regions coincident with these three sources, the spectra of parental particle population can extend up to at least several hundreds of TeV.

- Calculations of the energy budget for each source gives that the total energy required in protons \( W_{pp} = L_\gamma \times t_{pp} \), where \( t_{pp} = 5.76 \times 10^{15} \left( \frac{n_{\text{gas}}}{\text{cm}^{-3}} \right)^{-1} \) s is the cooling time for pp collisions) to produce the inferred \( \gamma \)-ray luminosity \( (L_\gamma) \) is:

  \[
  \text{HESS J1641–463} \rightarrow W_{pp} = 10^{48} \text{ erg and HESS J1826–130} \rightarrow W_{pp} = 10^{47} \text{ erg} \\
  \text{HESS J1741–302} \rightarrow W_{pp} = [7.0 \times 10^{46}, 1.5 \times 10^{48}] \text{ erg (depending on the cloud of interest)}
  \]

- It is not distinguishable whether the VHE emission from these sources has leptonic or hadronic origin. Taking into account the point-like morphologies of HESS J1641–463 and HESS J1741–302, binary scenarios can also be envisaged.

- A leptonic scenario, where electrons accelerated by the pulsar PSR J1826–1256 are up-scattering CMB or IR photons, can also explain the VHE emission from HESS J1826–130.

- This source has a spectrum very similar to other PWNe, in particular, Vela X. HESS J1826–130 could be an indication of a distinctive PWN population, with very hard spectra and relatively high cut-off energies.
Conclusions

• The analysis of the three sources presented here shows:

  - the common characteristic of very hard spectra (and coincident dense gas regions).

  - plausible scenarios where parental population of hadrons extends up to several hundreds of TeV.

• The latter result opens up the possibility that they may be representing a population of CR accelerators active in the Galaxy.

• Interpretations based on leptonic scenarios can not be discarded.

• The enhanced capabilities of CTA will allow us establishing if such a population of CR accelerators active in the Galaxy.
Differential γ-ray spectrum of HESS J1641–463 together with the expected emission from p–p collisions (left) and IC off CMB photons (right). The pink area represents the 1σ confidence region for the fit to a power-law model, the black data points the H.E.S.S. measured photon flux (1σ uncertainties), the arrows the 95% C.L. upper limits on the flux level, and the black curves the expected emission from the models, assuming different particle energy cutoff values. For comparison, the gray data points and curve represent the archival spectrum and the corresponding best-fit model, respectively, of SNR RX J1713.7–3946.