RECENT TOPICS IN TEV GAMMA-RAY ASTRONOMY

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Detection of gamma-rays

A \approx 10^4 \text{m}^2

\Omega \approx 10^{-2} \text{sr}

> TeV gamma-rays

Fermi Gamma-ray Space Telescope (2008 June-)
Cherenkov light from gamma-ray showers
Lateral distribution & Timing distribution
Imaging Atmospheric Cherenkov Telescope

Shower profile

Gamma 100 GeV gamma

Proton 300 GeV proton

→ Differentiation of gamma-rays from charged cosmic rays

Focal plane image

Gamma

Proton

Regular

Irregular

Sharp

Diffuse

α (image orientation angle)
Angular resolution
0.25deg → 0.1 deg

Energy resolution
30% → 15%

Better S/N (no local muons)
## Comparison of detection methods

<table>
<thead>
<tr>
<th>Base</th>
<th>Satellite</th>
<th>Ground</th>
<th>Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma-ray detection</td>
<td>Direct (pair creation)</td>
<td>Indirect (atmospheric Cherenkov)</td>
<td>Indirect (shower array)</td>
</tr>
<tr>
<td>Energy</td>
<td>&lt; 30 GeV (→ 100 GeV)</td>
<td>&gt;100 GeV (→ 50 GeV)</td>
<td>&gt;3 TeV (→ 1 TeV)</td>
</tr>
<tr>
<td>Pros</td>
<td>High S/N</td>
<td>Large area</td>
<td>24hr operation</td>
</tr>
<tr>
<td></td>
<td>Large FOV</td>
<td>Good Δθ</td>
<td>Large FOV</td>
</tr>
<tr>
<td>Cons</td>
<td>Small area</td>
<td>Low S/N (CR bkgd.)</td>
<td>Low S/N (CR bkgd.)</td>
</tr>
<tr>
<td></td>
<td>High cost</td>
<td>(but imaging overcomes this!)</td>
<td>Moderate Δθ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small FOV</td>
<td></td>
</tr>
</tbody>
</table>
Rene Ong, ICRC2005 OG2 rapporteur talk (updated)
Crab: the first TeV source

Whipple 10m telescope

37ch imaging camera

82hrs, 0.24\gamma/min
Crab Signal as seen in VERITAS in real time during commissioning

Weekes, Gamma2008, Heidelberg
TeV skymap
TeV skymap

2001
TeV skymap

2003

90°

180°

-180°

Jim Hinton
ICRC 2007
TeV skymap
TeV skymap
Increase of TeV sources

<table>
<thead>
<tr>
<th>Class</th>
<th>2003</th>
<th>2005</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PWN</strong> (Pulsar Wind Nebulae)</td>
<td>1</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td><strong>SNR</strong> (Subernova remnants)</td>
<td>2</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td><strong>Binary</strong></td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>Diffuse</strong></td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>AGN</strong> (Active Galactic Nuclei)</td>
<td>7</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td><strong>UnId</strong> (Unidentified sources)</td>
<td>2</td>
<td>6</td>
<td>21</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>12</td>
<td>33</td>
<td>71</td>
</tr>
</tbody>
</table>

“Kifune plot”
* Borders for SNR/PWN/UnID are vague…
H.E.S.S. Galactic survey

Survey region was extended in the years 2005 - 2007

-85° < l < 60° -2.5° < b < 2.5°

Hoppe 269

pure scan 400 h
Supernova remnants

- Long considered to be primary source for Galactic cosmic rays
- **Pros:**
  - Energetic enough (10% of SN explosion energy)
  - Size of object is large enough ($R \gg r_g$)
  - Many SNRs are bright radio sources: at least electrons are accelerated!
- **Cons:**
  - Magnetic fields too low to go beyond $10^{14}$eV
  - Additional problem: adiabatic losses
Shell SNRs seen at TeV

Comparable to PSF (0.09°)


Good keV-TeV Correlation!


F. Ahanorian et al., arXiv: 0803.0682/0702
Accelerated particles and gamma-ray spectrum

Proton

\[ \Pi^0 \text{ decay} \]

Flat spectrum above 100MeV

Electron

\[ \text{Synchrotron X-rays} \]

Inverse Compton gamma-rays

\[ \frac{p}{e} \text{ ratio problem} \]
Hard power-law + cutoff (?): $\sim E^{-2}\exp\left(-E/E_{\text{max}}\right)$

**SNR spectrum**

**Electron model**
- RX J1713.7-3946
- Aharonian et al. 2006
- Synchrotron
- Inverse Compton

**Proton model**
- RX J0842.0-4622
- Enomoto et al. 2006
- Synchrotron
- Inverse Compton

**NO definitive answer for accelerated particles!**
Identification of particles is not easy

Difficult in the GeV-TeV region if magnetic field is strong!

Fig. 12.—Pion-decay and IC emission for a range of $n_H$ and $B_0$. In the top panel, the heavy curves are pion decay, the light curves are IC, and $\epsilon_{\pi^0} = 36\%$ and $B_0 = 15 \, \mu G$ in all cases. The strong dependence of pion decay on ambient density $n_H$ is evident. The middle panel shows IC, and the bottom panel shows pion decay for $n_H = 0.1 \, \text{cm}^{-3}$, with $B_0$ varying from 3 $\mu G$ (solid curves) to 15 $\mu G$ (dashed curves) to 60 $\mu G$ (dotted curves). For comparison to the $\pi^0$, we show in the bottom panel the IC emission for $B_0 = 60 \, \mu G$ (light dotted curve). The particle distributions producing the emission in the bottom two panels are those shown in the top panel of Fig. 11.
Variation in ~1yr time scale
\[ \rightarrow \text{Need > 1mG! (locally)} \]
\[ \rightarrow \text{Protons produce TeV gamma-rays!} \]

Counter arguments: Y. Butt et al., arXiv:0801.4954
Evidence of proton acceleration?

IC443


W28

[H.E.S.S., Aharonian et al., A&A, in press]
SN1006

Chandra and H.E.S.S. Morphology

- Chandra map smoothed by the H.E.S.S. PSF and oversampled with 0.1°
- H.E.S.S. map with Chandra contours

- Independent analysis methods confirm the detection of the NE rim of SN 1006 at about 6 sigma in the region pre-defined in the 2004 H.E.S.S. upper limit paper
- Compatibility with non-thermal X-ray morphology very good
- Given the flux level of ~1% Crab, both leptonic and hadronic scenarios are reasonable

Naumann-Godó, Gamma 2008, Heidelberg
Major group in Galactic TeV sources
- 18/71 by Hinton (2007ICRC)
- Associated with relatively young (<10^5 years) and large spin-down pulsars

Extended $O(10\text{pc})$, displaced from pulsars

Gamma-rays via inverse Compton by electrons?
Pulsar nebula: energy-dependent morphology

- HESS J1825-137 associated with energetic pulsar
- Spectral steepening seen away from the pulsar
- Very likely this is evidence for cooling of electrons in the Nebula
  - Seen in several X-ray PWN
- A first in gamma-ray astronomy!
Simulations of Pulsar Wind Nebula

Displacement due to pulsar kick?
More pulsar nebulae...

Djannati-Atai et al., ICRC2007

Hoppe et al., ICRC2007

Carrigan et al., ICRC2007

Komin et al., ICRC2007


70.5ms PSR (ATel1392)
Pulsar nebulae and spin-down luminosity

Figure 3: Top: $P - \dot{P}$ diagram for pulsars: all ATNF pulsars (black), with detected X-ray PWN (brown), with a known corresponding SNR (blue), potentially associated to an EGRET source (green), associated to a H.E.S.S. VHE PWN (red). Bottom: Energy output for the selections used at the top.
Favors outer-gap model rather than polar-cap model
Gamma-ray binaries

LSI +61 303 (VERITAS/MAGIC)

$P_{\text{orb}} \approx 26.5\text{day}$

MAGIC

V.A. Acciari et al., arXiv:0802.2363

LS 5039 (H.E.S.S.)

$P_{\text{orb}} \approx 3.9\text{day}$

VERTAS

Gamma-ray binary: Cyg X-1

- Black hole binary: $M_{BH} \sim 21M_\odot$, $M_\star \sim 30M_\odot$
- Relativistic jet $v > 0.6c$: “microquasar”
- MAGIC 40hr obs.
- 4.9σ seen in one 79 min. time slice
- Estimated significance: 4.1σ after correction for statistical trials
Emission from binaries

Microquasar: particles (electrons or hadrons) are accelerated in a jet
Bosch-Ramon et al. (2006), Romero et al. (2007)

\( \text{\textgamma-ray produced in the shock}
\)
where the wind of the young pulsar
and the wind of the Be star collide
Dubus (2006), Dhawan et al. (2006)
Stellar cluster Westerlund 2

- Young open stellar cluster
  - Dozen O-stars
  - Two Wolf-Rayet stars (~80M☉ each)
- Extended gamma-ray emission covering (but offset from) Westerlund 2 by HESS
- Due to collective effects of stellar winds in the cluster?
- A new source class?


Churchwell 2004
Galactic center ≈ Sgr A*

HESS data 2003-2004 towards galactic centre. (We await 2005-6 data eagerly...)

Van Eldik et al., ICRC 2007

Energy spectrum is not consistent with dark matter annihilation signal!

Van Eldik 286

L. Bergström, CTA meeting, Jan. 2008

Steady (time-independent) spectrum, pointlike within HESS angular resolution, could be Moore cusp instead of NFW?

Shape of these curves uncertain, depends on QED corrections and fragmentation of 5-10 TeV jets. LHC should give important input here.
Galactic center ridge

After subtraction

Spectrum is harder than CR spectrum!

D=1.3 kpc²Myr⁻¹


Unidentified HESS sources

Two types:
1) No compelling counterparts
2) Dark in other wavelengths


TeV-GeV relation?

Coincident sources

<table>
<thead>
<tr>
<th>EGRET source</th>
<th>VHE X-ray source</th>
<th>Potential Counterpart</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Within the H.E.S.S. GPS</td>
<td></td>
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<tr>
<td>3EG J1639-4702</td>
<td>HESS J1640-465</td>
<td>G338.3-0.0 (SNR/PWN)</td>
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<tr>
<td>3EG J1744-3011</td>
<td>HESS J1745-303</td>
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</tr>
<tr>
<td>3EG J1800-2338</td>
<td>HESS J1801-233</td>
<td>W28 (SNR)</td>
</tr>
<tr>
<td>3EG J1826-1302</td>
<td>HESS J1825-137</td>
<td>G18.0-0.7 (PWN)</td>
</tr>
<tr>
<td>3EG J1824-1514</td>
<td>HESS J1826-148</td>
<td>LS 5039 (Binary)</td>
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<tr>
<td></td>
<td>Outside the H.E.S.S. GPS</td>
<td></td>
</tr>
<tr>
<td>3EG J0241+6103</td>
<td>MAGIC J0240+613</td>
<td>LSI+61 303 (Binary)</td>
</tr>
<tr>
<td>3EG J0617+2238</td>
<td>MAGIC J0616+225</td>
<td>IC443 (SNR/PWN)</td>
</tr>
<tr>
<td>3EG J0634+0521</td>
<td>HESS J0632+058</td>
<td>Monoceros</td>
</tr>
<tr>
<td>3EG J1420-6038</td>
<td>HESS J1420-607</td>
<td>Kookaburra (PWN)</td>
</tr>
</tbody>
</table>

![Graph showing TeV and GeV fluxes](chart.png)
Extended H.E.S.S. survey

Acceptance-corrected Exposure

Extended H.E.S.S. GPS
- $-85^\circ < l < 60^\circ$
- $-3^\circ < b < 3^\circ$
- Scan mode: 400 h
- Detected 50+ Galactic sources of VHE gamma-rays
- ICRC 2007, DPG 2008, Gamma08
H.E.S.S. galactic plane survey

H.E.S.S. GPS Significance Map

- HESS J1714-385 (SNR CTB 37A)
- HESS J1713-381 (SNR CTB 37B)
- HESS J1442-623 (SNR RCW 86)
- HESS J1356-654 (Offset PWN)
- HESS J1503-582 (FVW?)
- HESS J1848-018 (SFR W 43, WR 121a?)
- HESS J1849-000 (PWN)
## Extragalactic TeV sources

<table>
<thead>
<tr>
<th>Name</th>
<th>Discovered</th>
<th>Year</th>
<th>z</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 87</td>
<td>HEGRA</td>
<td>2003</td>
<td>0.004</td>
<td>VERITAS-Colin, HESS-Beilicke, MAGIC-Mazin</td>
</tr>
<tr>
<td>Mrk 421</td>
<td>Whipple</td>
<td>1992</td>
<td>0.031</td>
<td>MILAGRO-Smith, VERITAS-Fegan, TACTIC-Godambe, MAGIC-Paneque,</td>
</tr>
<tr>
<td>Mrk 501</td>
<td>Whipple</td>
<td>1996</td>
<td>0.034</td>
<td>MAGIC-Wagner</td>
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<tr>
<td>1ES 2344+514</td>
<td>Whipple</td>
<td>1998</td>
<td>0.044</td>
<td></td>
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<tr>
<td>Mrk 180</td>
<td>MAGIC</td>
<td>2006</td>
<td>0.046</td>
<td>MAGIC-Mazin</td>
</tr>
<tr>
<td>1ES 1959+650</td>
<td>TA</td>
<td>2002</td>
<td>0.047</td>
<td>MAGIC-Hayashida</td>
</tr>
<tr>
<td>BL Lac</td>
<td>MAGIC</td>
<td>2006</td>
<td>0.069</td>
<td>MAGIC-Hayashida</td>
</tr>
<tr>
<td>PKS 0548-322</td>
<td>HESS</td>
<td>2006</td>
<td>0.069</td>
<td>HESS-Superina</td>
</tr>
<tr>
<td>PKS 2005-489</td>
<td>HESS</td>
<td>2005</td>
<td>0.071</td>
<td>HESS-Costamante</td>
</tr>
<tr>
<td>PKS 2155-304</td>
<td>Durham</td>
<td>1999</td>
<td>0.116</td>
<td>HESS-Punch, CANGAROO-Sakamoto, VERITAS-Krawczynski</td>
</tr>
<tr>
<td>H 1426+428</td>
<td>Whipple</td>
<td>2002</td>
<td>0.129</td>
<td></td>
</tr>
<tr>
<td>1ES 0229+200</td>
<td>HESS</td>
<td>2007</td>
<td>0.140</td>
<td>HESS-Raue</td>
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<tr>
<td>H 2356-309</td>
<td>HESS</td>
<td>2005</td>
<td>0.165</td>
<td>HESS-Costamante</td>
</tr>
<tr>
<td>1ES 1218+304</td>
<td>MAGIC</td>
<td>2005</td>
<td>0.182</td>
<td>MAGIC-Hayashida</td>
</tr>
<tr>
<td>1ES 1101-232</td>
<td>HESS</td>
<td>2005</td>
<td>0.186</td>
<td>HESS-Puelhofer</td>
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<tr>
<td>1ES 0347-121</td>
<td>HESS</td>
<td>2007</td>
<td>0.188</td>
<td>HESS-Raue</td>
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<tr>
<td>1ES 1011+496</td>
<td>MAGIC</td>
<td>2007</td>
<td>0.212</td>
<td>MAGIC-Mazin</td>
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<td>PG 1553+113</td>
<td>HESS/MAGIC</td>
<td>2005</td>
<td>?</td>
<td>MAGIC-Wagner, HESS-Benbow</td>
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<tr>
<td>3C 279</td>
<td>MAGIC</td>
<td>2007</td>
<td>0.536</td>
<td>MAGIC-Teshima</td>
</tr>
</tbody>
</table>
Emission from AGNs

FSRQ
BL Lac

Electron model
Fossati et al. 1998

Proton model
Muecke et al. APh 18, 2003
Fast time variation

PKS 2155−304

\( z = 0.116 \)

July 28, 2006

Peak flux \( \sim 15 \times \text{Crab} \)

\( \sim 50 \times \text{average} \)

Luminosity \( \sim 10^{12} \times \text{Crab} \)

Doubling times

67, 116, 173, 178 ±50 s

\( R_{\text{BH}}/c \sim 1...2 \times 10^4 \text{ s} \)

Suzaku

M. Hayashida, ICRC 2007

H.E.S.S.

W. Hofmann, TAUP 2007

\( \text{preliminary} \)

Fast variation \( \leftrightarrow \) Acceleration site & mechanism
Observed spectrum is affected by integalactic absorption!

\[ \gamma_{\text{TeV}} + \gamma_{\text{IR}} \rightarrow e^+ + e^- \]

Mean free path for $e^+e^-$ pair production


Jim Hinton, rapporteur talk, ICRC 2007

We cannot discriminate source spectrum and integalactic absorption!
Assume not harder than $E^{-1.5}$

Some models can be rejected
Background IR intensity limited by TeV observations

Upper limits: fluctuation/direct measurements
Lower limits: source counts
3C279 at $z=0.538$

**Fig. 1.** Light curves. MAGIC (top) and optical R-band data (bottom) obtained for 3C 279 from February to March 2006. The long-term baseline for the optical flux is at 0 mJy.

**Fig. 2.** Spectrum of 3C 279 measured by MAGIC. The gray area includes the combined statistical (1σ) and systematic errors, and underlines the marginal significance of detections at high energy. The dotted line shows compatibility of the measured spectrum with a power law of photon index $\alpha = 4.1$. The blue and red triangles are measurements corrected on the basis of the two models for EBL density, discussed in the text.
Redshift distribution of blazars

Model Fit to Blazar Redshift Distribution

Fit parameters for the FSRQs are $\Gamma = 8$ and comoving directional luminosity $L = 10^{40}$ ergs sr$^{-1}$ s$^{-1}$; EC statistics

Fit parameters for the BL Lacs are $\Gamma = 5$ and $L = 10^{42}$ ergs sr$^{-1}$ s$^{-1}$; syn/SSC statistics
Redshift distribution of blazars

More AGNs as energy threshold goes lower!
Clusters of galaxies: upper limits

H.E.S.S.: Domainko et al., ICRC2007

Perseus

A496

A3667

Coma

A4038


CANGAROO-III: Kiuchi et al., ICRC2007
Gamma-ray skymap

(background: Fermi Gamma-ray Space Telescope Firstlight data [>100 MeV])
Under construction

H.E.S.S. II

MAGIC II

28m

85m
Future projects

CTA (Cherenkov Telescope Array): EU++

AGIS (Advanced Gamma-ray Imaging System): USA++

Option:
Mix of telescope types

~10 central Huge telescopes

~100 Medium + Small Telescopes

(by J. Buckley, Wash.U.)

Picture: Courtesy of W. Hofmann
log N-log S relation

$N \propto S^{-2/3}$

$\times 2$ (North/South)

↓

1000 TeV sources if mCrab!

Data: H.E.S.S. catalog
High energy window of the Universe is now open!
- Additional 2-3 decades of the photon spectrum
- Wider variety of sources than expected
  → Cosmic accelerators are ubiquitous!
- Much work left to understand their physics
- Also: cosmology, fundamental physics

Hoping to detect other class of sources…
- Pulsars
- Star-forming galaxies, mergers
- Dwarf galaxies and dark matter
- Ultraluminous IR galaxies
- Clusters of galaxies
- Gamma-ray bursts
Thank you!

CANGAROO-III telescopes, Woomera, South Australia
Gamma-ray signal from DM annihilation at the Galactic center

Indirect detection through $\gamma$-rays.
Three types of signal:

- Continuous from $\pi^0$, $K^0$, ... decays and
- Monoenergetic line and
- Internal bremsstrahlung from QED process.

Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)

Good spectral signatures!
Unfortunately, large uncertainties in the predictions of absolute rates

L.B., P.Ullio & J. Buckley 1998