Masaki Mori

Institute for Cosmic Ray Research,
University of Tokyo

International Workshop on Advances in Cosmic Ray Science
March 17-19, 2008, Waseda University, Shinjuku, Tokyo, Japan
Detection of gamma-rays

$A \sim 10^4 m^2$

$\Omega \sim 10^{-2} sr$

$\sim 1 m^2$

$\sim \pi sr$

$\sim 10^{-2} sr$

TeV gamma-rays

Air shower
Atmospheric Cherenkov Telescope

Cherenkov light from gamma-ray showers
Lateral distribution & Timing distribution

- Primary photon
  - $E_0 = 100$ GeV
  - $H_0 = 3.5$ km
  - $H_0 = 2.2$ km
  - $H_0 = 0$ km

- Delay [ns]

- Core distance [m]

- Photon density [photon/m$^2$]
Imaging Atmospheric Cherenkov Telescope

Shower profile

- Gamma
  - 100 GeV gamma
  - Regular

- Proton
  - 300 GeV proton
  - Irregular

Focal plane image

- Gamma
  - Sharp
  - Field of view of a telescope (about 3 degrees)

- Proton
  - Diffuse

→ Differentiation of gamma-rays from charged cosmic rays
Stereoscopic observation of Cherenkov light

Angular resolution
0.25deg → 0.1 deg

Energy resolution
30% → 15%

Better S/N (no local muons)

© S.Funk, 2005

~10km

θ² distribution
(Simulation)

Entries/bin

θ² [deg²]

© S.Funk, 2005
# Comparison of detection methods

<table>
<thead>
<tr>
<th>Base</th>
<th>Satellite</th>
<th>Ground</th>
<th>Ground</th>
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</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 ($\rightarrow 100$ GeV)</td>
<td>$&gt;100$ GeV ($\rightarrow 50$ GeV)</td>
<td>$&gt;3$ TeV ($\rightarrow 1$ 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 $\Delta \theta$</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>
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<tr>
<td></td>
<td>High cost</td>
<td>(but imaging overcomes this!)</td>
<td>Moderate $\Delta \theta$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small FOV</td>
<td></td>
</tr>
</tbody>
</table>
TeV skymap

1999

90°

180°

-180°

Jim Hinton
ICRC 2007
TeV skymap

2001

90°

180°

RX J1713.7-3946

Jim Hinton
ICRC 2007
TeV skymap

2003

90°

180°

-180°

PWNe

Unidentified

SNRs

AGNs

Whipple

Durham

HEGRA

CANGAROO

TA

HESS

MAGIC

Milagro

RX J1713.7-3946

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

Jim Hinton, rapporteur talk, ICRC 2007

## “Kifune plot”

<table>
<thead>
<tr>
<th>Class</th>
<th>2003</th>
<th>2005</th>
<th>2007</th>
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</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>
TeV sources classified

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

Survey region was extended in the years 2005 - 2007

pure scan
400 h

-85° < l < 60°  -2.5° < b < 2.5°
H.E.S.S. Galactic survey

Significance of $\gamma$-ray excess

Preliminary

Galactic Centre

New sources found in the survey data

Saturated at 20°
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 \((R >> r_g)\)
  - 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

Jim Hinton, rapporteur talk, ICRC 2007
Accelerated particles and gamma-ray spectrum

- Proton:
  - $\Pi^0$ decay
  - Flat spectrum above 100MeV

- Electron:
  - Synchrotron X-rays
  - Inverse Compton gamma-rays

$E^2 dF/DE$ vs Energy (TeV)

©A.Bamba
Hard power-law + cutoff (?): $\sim E^{-2}\exp(-E/E_{\text{max}})$

**SNR spectrum**

Electron model

Proton model

RX J1713.7-3946

Aharonian et al. 2006

Berezhko & Voelk 2007

RX J0842.0-4622

Enomoto et al. 2006

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

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 $\epsilon_{\pi\ell} = 36\%$ 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.

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

Variation in ~1yr time scale

→ Need > 1mG ! (locally)

→ Protons produce TeV gamma-rays!?

Counter arguments: Y. Butt et al., arXiv:0801.4954

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**RX J1713.7-3946 by Chandra**

**SNR** | Dist (kpc) | $V_s$ (km s$^{-1}$) | $n_0$ ($\text{cm}^{-3}$) | Width (") | $B_{\text{loss}}$ ($\mu$G) | $B_{\text{diss}}$ ($\mu$G) |
<table>
<thead>
<tr>
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<th></th>
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<td>Cas A</td>
<td>3.4</td>
<td>5200</td>
<td>3</td>
<td>0.5</td>
<td>249</td>
<td>299</td>
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<tr>
<td>Kepler</td>
<td>4.8</td>
<td>5300</td>
<td>0.35</td>
<td>1.5</td>
<td>97</td>
<td>113</td>
</tr>
<tr>
<td>Tycho</td>
<td>2.4</td>
<td>4500</td>
<td>0.3</td>
<td>2</td>
<td>113</td>
<td>165</td>
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<td>SN1006</td>
<td>2.2</td>
<td>4300</td>
<td>0.1</td>
<td>20</td>
<td>30</td>
<td>39</td>
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<tr>
<td>RCW86</td>
<td>2.5</td>
<td>3500</td>
<td>0.1</td>
<td>45</td>
<td>24</td>
<td>14</td>
</tr>
</tbody>
</table>
SNRs interacting with clouds?

IC443

[X-ray, 20cm, 12CO]


W28

[X-ray, 90cm]

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

Evidence of proton acceleration?
Pulsar nebulae

- 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!
More pulsar nebulae...

HESS J1833-105
Djannati-Atai et al., ICRC2007

HESS J1846-029
Komin et al., ICRC2007

HESS J1912+012
Hoppe et al., ICRC2007

HESS J1718-385
Carrigan et al., ICRC2007

HESS J1809-193

HESS J1837-069

70.5ms PSR (ATel1392)
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.
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

VERITAS


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

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

Gamma-ray binary: Cyg X-1

- Black hole binary: $M_{\text{BH}} \sim 21M_\odot$, $M_\star \sim 30M_\odot$
- Relativistic jet $v > 0.6c$: “microquasar”
- MAGIC 40hr obs.
- 4.9$\sigma$ seen in one 79 min. time slice
- Estimated significance: 4.1$\sigma$ 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)

γ-rays 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)
Young open stellar cluster
- Dozen O-stars
- Two Wolf-Rayet stars (~80$M_\odot$ 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 \(\approx \text{Sgr A*}\)

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!

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

But: Probably too high energy (and wrong shape of spectrum) for WIMP annihilation explanation

Van Eldik 286

VLA 90cm radio image

Sgr A East

Sgr A*

1 sigma total error circle

Energy spectrum is not consistent with dark matter annihilation signal!
Spectrum is harder than CR spectrum!

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 γ-ray source</th>
<th>Potential Counterpart</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Within the H.E.S.S. GPS</td>
<td></td>
</tr>
<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>
<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>
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<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>
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<tr>
<td>3EG J0241+6103</td>
<td>MAGIC J0240+613</td>
<td>LSI+61 303 (Binary)</td>
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<tr>
<td>3EG J0617+2238</td>
<td>MAGIC J0616+225</td>
<td>IC443 (SNR/PWN)</td>
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<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>

GLAST
H.E.S.S.
EGRET

log(10)(Energy Flux (ergs cm⁻² s⁻¹))
# Extragalactic TeV sources

<table>
<thead>
<tr>
<th>Name</th>
<th>Discovered</th>
<th>Year</th>
<th>z</th>
<th>Contributions</th>
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<tbody>
<tr>
<td>M 87</td>
<td>HEGRA</td>
<td>2003</td>
<td>0.004</td>
<td>VERITAS-Colin, HESS-Beilicke, MAGIC-</td>
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<tr>
<td>Mrk 421</td>
<td>Whipple</td>
<td>1992</td>
<td>0.031</td>
<td>MILAGRO-Smith, VERITAS-Fegan, +</td>
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<tr>
<td>Mrk 501</td>
<td>Whipple</td>
<td>1996</td>
<td>0.034</td>
<td>TACTIC-Godambe, MAGIC-Paneque, +</td>
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<tr>
<td>1ES 2344+514</td>
<td>Whipple</td>
<td>1998</td>
<td>0.044</td>
<td>MAGIC-Wagner</td>
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<tr>
<td>Mrk 180</td>
<td>MAGIC</td>
<td>2006</td>
<td>0.046</td>
<td>MAGIC-Mazin</td>
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<tr>
<td>1ES 1959+650</td>
<td>TA</td>
<td>2002</td>
<td>0.047</td>
<td>MAGIC-Hayashida</td>
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<tr>
<td>BL Lac</td>
<td>MAGIC</td>
<td>2006</td>
<td>0.069</td>
<td>MAGIC-Hayashida</td>
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<tr>
<td>PKS 0548-322</td>
<td>HESS</td>
<td>2006</td>
<td>0.069</td>
<td>HESS-Superina</td>
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<tr>
<td>PKS 2005-489</td>
<td>HESS</td>
<td>2005</td>
<td>0.071</td>
<td>HESS-Costamante</td>
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<tr>
<td>PKS 2155-304</td>
<td>Durham</td>
<td>1999</td>
<td>0.116</td>
<td>HESS-Punch, CANGAROO-Sakamoto, +</td>
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<td>H 1426+428</td>
<td>Whipple</td>
<td>2002</td>
<td>0.129</td>
<td>VERITAS-Krawczynski</td>
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<td>MAGIC-Hayashida</td>
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<td>1ES 1101-232</td>
<td>HESS</td>
<td>2005</td>
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<td>HESS-Puelhofer</td>
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<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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<td>3C 279</td>
<td>MAGIC</td>
<td>2007</td>
<td>0.536</td>
<td>MAGIC-Teshima</td>
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</table>

8 new AGN
Emission from AGNs

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 $\sim 15 \times$ Crab
$\sim 50 \times$ average
Luminosity $\sim 10^{12} \times$ Crab
Doubling times
$67, 116, 173, 178 \pm 50 \text{ s}$

$R_{BH}/c \sim 1\ldots 2 \times 10^4 \text{ s}$

H.E.S.S.

W. Hofmann,
TAUP 2007

Suzaku

M. Hayashida,
ICRC 2007

M.G.C.

Fast variation $\leftrightarrow$ Acceleration site & mechanism

preliminary
Observed spectrum is affected by intergalactic absorption!

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

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

We cannot discriminate source spectrum and intergalactic absorption!

Jim Hinton, rapporteur talk, ICRC 2007

Unfolding source spectra

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

3C 279: One night, 23rd Feb 2006

- 6.1 σ in low Energy band
  - Post-trails?
- 5.1 σ >220 GeV
  - Surprising!

Sky map around 3C279

E> 220 GeV Preliminary

Significance: 6.13 σ

Significance: 5.07 σ

Preliminary

80-220 GeV

Excesses: 624.36 Preliminary

Preliminary
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

C. Dermer, GLAST LAT AGN Science Group meeting, March 4, 2006
Redshift distribution of blazars

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

Perseus

A2029

42d 00m
42d 40m
41d 20m
41d 00m

03h 21m
03h 18m

Right Ascension (J2000)

0.05
0.18
0.15

X (3C 83.1)
X (3C 84.0)
(3C 310)

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

Coma

A496

-12.00
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00

Preliminary

A3667

-56.00
-57.00
-58.00
-59.00
-60.00
-61.00
-62.00
-63.00

304
303
302

CANGAROO-III: Kiuchi et al., ICRC2007

A4038

-28.00
-29.00
-30.00
-31.00
-32.00
-33.00
-34.00

356.00
356.50
357.00
357.50
358.00

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