最近の高エネルギーガンマ線天文学の発展

Recent developments in high-energy gamma-ray astrophysics

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2006年11月9日
Detection of gamma-rays (1)

A $\sim 10^4$ m$^2$

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

$\gg$ TeV gamma-rays
Atmospheric Cherenkov telescopes

Cherenkov light from gamma-ray showers

Lateral distribution & Timing distribution
Atmospheric transmission

MODRAN4 calculation by M. Yuasa (2006)

MODRAN4 calculation by H. Tsunoo (2002)
Imaging Cherenkov Telescopes

Shower profile

Gamma 100 GeV gamma
Regular

Proton 300 GeV proton
Irregular

Focal plane image

Gamma Sharp
Proton Diffuse

Image parameters of a shower

Field of view of a telescope (about 3 degrees)

\( \alpha \) (image orientation angle)
Imaging analysis

Distribution of imaging parameters

α (image orientation angle)

“Image parameters”: A.M. Hillas, 1983 ICRC


WhippleによるCrabの検出

82hrs, 0.24\(\gamma\)/min

WhippleによるMrk421の検出

ガンマ線信号

Stereo observation

Angular resolution
0.25$\text{deg} \rightarrow 0.1$ deg

Energy resolution
30$\% \rightarrow 15\%$

Better S/N (no local muons)

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## Detection of gamma-rays (2)

<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</td>
<td>Indirect (shower array)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cherenkov)</td>
<td></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>
</tr>
<tr>
<td></td>
<td>High cost</td>
<td><em>(but imaging overcomes this!)</em></td>
<td>Moderate $\Delta\theta$</td>
</tr>
</tbody>
</table>
Table 1. Currently operating VHE gamma-ray telescopes. The name of each telescope is given, along with its type (AC=Atmospheric Cherenkov), location, altitude, specifications, and reference at this meeting. The specifications list the currently installed detector area (mirror area for atmospheric Cherenkov and instrumented detector area for air shower). There is no reference at this meeting for the CACTUS telescope.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Location</th>
<th>Altitude</th>
<th>Specifications</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CACTUS</td>
<td>AC-Sampling</td>
<td>Barstow, USA</td>
<td>640 m</td>
<td>144 x 42 m²</td>
<td>[5]</td>
</tr>
<tr>
<td>CANGAROO-III</td>
<td>AC-Imaging</td>
<td>Woomera, Australia</td>
<td>165 m</td>
<td>4 x 57 m²</td>
<td>[6]</td>
</tr>
<tr>
<td>HESS</td>
<td>AC-Imaging</td>
<td>Gamsberg, Namibia</td>
<td>1800 m</td>
<td>4 x 110 m²</td>
<td>[7]</td>
</tr>
<tr>
<td>MAGIC</td>
<td>AC-Imaging</td>
<td>La Palma, Spain</td>
<td>2250 m</td>
<td>1 x 226 m²</td>
<td>[8]</td>
</tr>
<tr>
<td>PACT</td>
<td>AC-Sampling</td>
<td>Pachmarhi, India</td>
<td>1075 m</td>
<td>25 x 4.5 m²</td>
<td>[9]</td>
</tr>
<tr>
<td>SHALON</td>
<td>AC-Imaging</td>
<td>Tien Shan, Kazakhstan</td>
<td>3338 m</td>
<td>1 x 11 m²</td>
<td>[10]</td>
</tr>
<tr>
<td>STACEE</td>
<td>AC-Imaging</td>
<td>Albuquerque, USA</td>
<td>1700 m</td>
<td>64 x 37 m²</td>
<td>[11]</td>
</tr>
<tr>
<td>TACTIC</td>
<td>AC-Imaging</td>
<td>Mt. Abu, India</td>
<td>1400 m</td>
<td>1 x 9.5 m²</td>
<td>[12]</td>
</tr>
<tr>
<td>VERITAS</td>
<td>AC-Imaging</td>
<td>Mt. Hopkins, USA</td>
<td>1275 m</td>
<td>2 x 110 m²</td>
<td>[13]</td>
</tr>
<tr>
<td>Whipple</td>
<td>AC-Imaging</td>
<td>Mt. Hopkins, USA</td>
<td>2250 m</td>
<td>1 x 78 m²</td>
<td></td>
</tr>
<tr>
<td>ARGO-YBJ</td>
<td>Air Shower</td>
<td>Yangbajing, Tibet</td>
<td>4300 m</td>
<td>4000 m²</td>
<td>[14]</td>
</tr>
<tr>
<td>GRAPES-III</td>
<td>Air Shower</td>
<td>Ooty, India</td>
<td>2200 m</td>
<td>288 x 1 m²</td>
<td>[15]</td>
</tr>
<tr>
<td>Milagro</td>
<td>Air Shower</td>
<td>Los Alamos, USA</td>
<td>2630 m</td>
<td>4800 m²</td>
<td>[16]</td>
</tr>
<tr>
<td>Tibet</td>
<td>Air Shower</td>
<td>Yangbajing, Tibet</td>
<td>4300 m</td>
<td>761 x 0.5 m²</td>
<td>[17]</td>
</tr>
</tbody>
</table>
H.E.S.S.

- 107 m² mirror area
  - 380 individual facets
- 15 m focal length
- 60 t structure
- Alt-Az mount

- 4 x 960 x 0.16° PMTs → 5° field of view
- Integrated readout electronics
- 2-telescope coincidence
MAGIC-I & MAGIC-II

17m diameter largest dish
High resolution camera
Ultra fast read out system 300M → 2GHz
Analogue signal fiber transmission

MAGIC-II is under construction and will be completed in the fall of the next year
CANGAROO-III

- Location:
  - 31°06'S, 136°47'E
  - 160m a.s.l.

- Telescope:
  - 114×80cmφ FRP mirrors (57m², Al surface)
  - 8m focal length
  - Alt-azimuth mount

- Camera:
  - T1: 552ch (2.7° FOV)
  - T2,T3,T4: 427ch (4° FOV)

- Electronics:
  - TDC+ADC

http://icrhp9.icrr.u-tokyo.ac.jp
Galactic sources: basics

- Supernova remnants = Origin of CR?
  - Energetics – OK (if 10% of $E_{SN}$ goes to CR)
  - Maximum energy – Up to “Knee region”
  - How much of them?
  - Some evidences, which can be ascribed to HE electrons: where are HE protons?

- Pulsar and pulsar wind nebula (plerions)
  - Crab – “The standard candle”
    - Up to a few 10GeV: pulsed+unpulsed
    - Above: unpulsed only
    - Unpulsed: SSC (Synchrotron-Self-Compton) model
    - Where is the cutoff?
    - (Pulsar emission models)

- Others?
Particle acceleration in SNR

Non-linear kinetic theory

\[ t_0 = \frac{R_0}{v_0}; \text{ sweep up time} \]

Particle spectrum

Maximum momentum

Berezhko & Voelk, APh 1997

Cf. Lagage and Cesarsky 1984
Nuclear gamma-ray flux from SNR

Berezhko & Voelk, APh 1997
Gamma-ray emission from SNR


n=10 cm⁻³

n=1 cm⁻³

n=0.1 cm⁻³

e/p = 0.01  0.1  1

Dot: IC
Dash: π⁰
Dot-dash: brems
(Data: EGRET IC443)
A shock is formed when pulsar wind balances with ambient gas pressure, and the wind shines by synchrotron emission by thermalization.
The Crab

Optical + X-ray image

Inner ring = Shock front

Crab (pulsed)

Crab (unpulsed)

Synchrotron Self Compton

Asahara et al., SPIE 2002
“Known” galactic sources:

Supernova remnants

- **Crab** “The standard candle”
  - Well established (many observations since 1989)

- **Supernova remnant RX J1713.7-3946**

- **Supernova remnant Cas A**
  - HEGRA CT system 2001

- **Supernova remnant RX J0852.0-4622**
  - CANGAROO 2005, H.E.S.S. 2005

- **Supernova remnant Vela X** [H.E.S.S. 2006, CANGAROO 2006]

- **Possible SNRs**: G338.3-0.0, G8.7-0.1, G18.0-0.7, G23.3-0.3, G25.5+0.0, AX J1813-178 [H.E.S.S. 2005]

- **Pulsar PSR 1706-44, Vela pulsar, SN1006**
  - CANGAROO-I claims, but H.E.S.S. upper limits
SNR RX J1713.7-3946 (1)

- Detected in X-rays
- Non-thermal X-ray spectrum

Significance map

Energy spectrum

Gamma-ray signal = (ON) – (OFF)

SNR RX J1713.7-3946 (2)

Hard to explain by emission from electrons (Brems, IC)

$\Rightarrow$ Emission from protons ($\pi^0$)?

$\Rightarrow$ Cosmic ray origin?

NANTEN results:
Distance $\sim$ 1 kpc
Age $\sim$ 1600 yr
$\Rightarrow L_p$ $\sim$ $10^{48}$ erg $\sim$ 0.001 $L_{SN}$

(Fukui et al. PASJ 55, 2003)
SNR RX J1713.7-3946 (3)

Counter arguments

* Butt et al., Nature 418 (2002) 489
Fig. 9. Morphology of RX J1713.7–3946 as it appears at different energies. Shown from left to right are gamma-ray excess images with energies of $E < 0.6$ TeV, $0.6$ TeV $< E < 1.4$ TeV, and $1.4$ TeV $< E$. Drawn additionally as white lines are contours of significance, linearly spaced at 5, 10, 15$\sigma$ (as in Fig. 7). Note the increase in the signal-to-noise ratio with increasing energy. The energy bands were chosen such that each band represents about a third of the full data set (taking events after cuts). Furthermore, all three images were smoothed with a Gaussian of 2$'$, which makes them directly comparable to each other, and to Fig. 7. The resolution in each energy band is indicated in the lower left hand corner of the images; the three data subsets have comparable resolutions of $\approx 0.08^\circ$ (the resolution of the intermediate energy band is about 6% better). This might be counter-intuitive, given that at larger energies camera images get bigger and fluctuation effects become negligible thereby improving the energy and direction resolution. However, in this case that effect is compensated by the increasing mean zenith angle of the large-energy events.
Fig. 17. Left panel: Shown are the intensity distribution of CO ($J = 1-0$) emission (Fukui et al. 2003) (linear colour scale in units of K km s$^{-1}$, truncated at a value of 23 to highlight important features), derived by integrating the CO spectra in the velocity range from $-11$ km s$^{-1}$ to $-3$ km s$^{-1}$ (which corresponds to 0.4 kpc to 1.5 kpc in space). Overlaid are coloured contours of the H.E.S.S. gamma-ray excess image. The levels are labelled and linearly spaced at 30, 60, and 90 counts. Note that the image is shown in Galactic coordinates. Right panel: Azimuth profile plot, that is, number of counts as a function of the azimuthal angle, integrated in a 0.2$^\circ$-wide ring covering the shell of RX J1713.7–3946 (dashed yellow circle in the left-hand panel). Plotted are the H.E.S.S. gamma-ray and the NANTEN data set.
SNR RX J1713.7-3946 (6)

Electron origin model

Proton origin model

Fig. 19. Broadband SED of RX J1713.7-3946. The ATCA radio data and ASCA X-ray data (Hiraga 2005) for the whole SNR are indicated, along with the H.E.S.S. measurement and the EGRET upper limit. Note that the radio flux was determined in Lazendic et al. (2004) for the northwest part of the shell only and was scaled up by a factor of two here to account for the whole SNR. The synchrotron and IC spectra were modelled assuming a source distance of 1 kpc, an age $T$ of 1000 years, a density $n$ of 1 cm$^{-3}$, and a production rate of relativistic electrons by the acceleration mechanism in the form of a power law of index $\alpha = 2$ and an exponential cutoff of $E_0 = 10^{10}$ TeV. Shown are three curves for three values of the mean magnetic field: 7 $\mu$G, 9 $\mu$G, and 11 $\mu$G, to demonstrate the required range of the B field strength for this scenario. The electron luminosity is adopted such that the observed X-ray flux level is well matched. For the three magnetic field values the luminosity $L_e$ is $L_e = 1.77 \times 10^{37}$ erg s$^{-1}$ (7 $\mu$G), $L_e = 1.14 \times 10^{37}$ erg s$^{-1}$ (9 $\mu$G), and $L_e = 0.81 \times 10^{37}$ erg s$^{-1}$ (11 $\mu$G).

Fig. 20. H.E.S.S. data points plotted in an energy flux diagram. They shaded grey band is the systematic error band for this measurement (see Sect. 3.2). The black curve is the best fit of a power law with exponential cutoff to the data, extrapolated to lower energies. The dashed blue curves is the same function, but it takes the $\pi^0$ kinematics into account. The EGRET upper limit from 1 GeV to 10 GeV is plotted as red arrow.

$\Rightarrow$ Protons favored (?)
SNR RX J1713.7-3946 (7)

Fig. 14. The image illustrates the results of the spatially resolved spectral analysis. **Left part:** Shown in red are gamma-ray excess contours from Fig. 7, linearly spaced at 30, 60, and 90 counts. Superimposed are the 14 boxes (each 0.26° × 0.26° in dimension) for which spectra were obtained independently. The dashed line is the 0.65° radius circle that was used to integrate events to produce a spectrum of the whole SNR. The photon index obtained from a power-law fit in each region is colour coded in bins of 0.1. The ranges of the fits to the spectra have been restricted to a maximum of 8 TeV (see Table 2). **Right part:** Plotted is the integral flux above 1 TeV against the photon index, for the 14 regions the SNR was sub-divided in. The error bars are ±1σ statistical errors. Note that systematic errors of 25% on the flux and 0.1 on the photon index are to be assigned to each data point additionally.
SNR RX J0852.0-4622 [G266.2-1.2, Vela Jr.] (1)

Figure 1. Recent all-sky survey images of the Vela SNR and its surroundings. Angular resolution is 1 arcmin half power radius; mean exposure is 983 s. The left-hand image was taken for photon energies 0.1 < E < 2.4 keV; surface brightness increases from dark yellow to white by a factor of 500. The right-hand image is for photon energies >1.3 keV. Most of the Vela SNR X-ray emission which dominates at low energies had disappeared. At the centre, the synchrotron nebula around the Vela pulsar remains visible as well as the SSW beam-like structure, and at the very northwest (upper right) the bright Puppis A SNR can be seen. The new shell-type SNR RX J0852.0—4622 shows up in the lower left. East of RX J0852.0—4622 hard X-ray photons from the D/V Vela SNR shrapnels are seen which, however, are associated with a much lower temperature spectrum than RX J0852.0—4622 (ref. 14). For X-ray spectral analysis, RX J0852.0—4622 was divided into two regions, one containing the bright northern limb section (l) and the other one (r) excluding the northern and southern limbs. Spectral fits were performed with either power-law models, optically thin thermal emission equilibrium models (Raymond-Smith models) or combinations of both. Solutions with a reduced \( \chi^2 < 1 \) for region r are obtained only with a two-temperature model with \( kT_{e1} = 0.14^{+0.05}_{-0.04} \) keV, \( kT_{e2} = 2.6^{+0.2}_{-0.1} \) keV. The spectrum of the northern limb can be fitted by either a simple power law with index \( \alpha = -2.9^{+0.3}_{-0.2} \) or a two-temperature model with \( kT_{e1} = 0.21^{+0.06}_{-0.05} \) keV, \( kT_{e2} = 4.7^{+0.5}_{-0.3} \) keV. The presence of low-temperature components may partially be due to a residual, uncorrected contribution from the much softer Vela SNR. The total, absorption-corrected flux of the high-temperature components is \( F_{\alpha}(0.1-2.4\text{keV}) = 3 \times 10^{-9} \text{ erg cm}^{-2} \text{s}^{-1} \).
SNR RX J0852.0-4622 (2)


H.E.S.S.: Aharonian et al., AA 437, L7 (2005)

Fig. 2. Count map of $\gamma$-rays from the direction of RX J0852.0-4622 after background subtraction. The data are smoothed with a Gaussian ($\sigma = 0.1^\circ$) representing the angular resolution of the instrument. The point spread function (PSF) is indicated by a circle. $\gamma$-ray features smaller than the PSF should not be considered as real. The lines denote equidistant contours of smoothed ($\sigma = 0.1^\circ$) X-ray data from the ROSAT All Sky Survey, with energies restricted to above 1.3 keV. The position of the neutron star candidate AX J0851.9-4617.4 is marked with an asterisk. The axes show J2000.0 equatorial coordinates.
SNR RX J0852.0-4622 (3)

$E^2 \frac{d\Phi}{dE}$ (eV cm$^{-2}$ s$^{-1}$)

Photon energy $E$ (eV)


H.E.S.S.: Aharonian et al., AA 437, L7 (2005)
SNR RX J0852.0-4622 (4)

- Stereo (T2 & T3 & T4 wobble)
- 1,129 min. ON, 1,081 min OFF (2005 Jan/Feb)
- Independent analysis (ICRR, Kyoto)

Fisher discriminant

$\theta^2$ from SNR center

Excess event map
SNR RX J0852.0-4622 (5)

\[ \frac{dF}{dE} = [2.5 \pm 0.6 \text{(stat.)} \pm 0.6 \text{(sys.)}] \times 10^{-11} \cdot \left( \frac{E}{1 \text{ TeV}} \right)^{2.2 \pm 0.3 \text{(stat.)} \pm 0.3 \text{(sys.)}} \text{[cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}] \]

Comparison with C-II

Fig. 7.— Differential energy spectra; the red points by H.E.S.S. are for the whole remnant and the black points from these CANGAROO-III observations are also for the whole remnant. The error bars are statistical.
SNR G0.9+0.1

- Compatible with a point source
- Position compatible with the PWN position
- Emission not consistent with the SNR shell

230 hr, 500 pointings
14 new TeV sources + 3 known

Scale height
\(~ 0.3\) deg RMS
\(~\) molecular gas
There are many SNRs!

231 SNRs

 Supernova Remnants (Green 2004)

35 New SNRs by Brogan et al. (2006)

Total >300 SNRs?

“New” galactic sources

- The **Galactic center**

- Pulsar wind nebulae
  - **MSH15-52** [CANGAROO 2000, H.E.S.S. 2005]
  - **Vela X** [H.E.S.S. 2005, CANGAROO 2006]

- Pulsar binary **PSR 1259-63/SS2883**
  - H.E.S.S. 2005

- X-ray binary/microquasar
  - **LS5039** [H.E.S.S. 2005, 2006]
  - **LS I +61 303** [MAGIC 2006]

- **UnID**
  - HEGRA J2032+4130
  - H.E.S.S. J1303-631
  - New H.E.S.S. sources
The Galactic center [Sgr A*]


Dark matter signal from Sgr A*?

Neutralino-type dark matter:

Kaluza-Klein dark matter:
**Not dark matter signal from Sgr A***?**

FIG. 2: (Color online) Spectral energy density $E^2 \times dN/dE$ of $\gamma$-rays from the GC source, for the 2004 data (full points) and 2003 data (open points). Upper limits are 95% CL. The shaded area shows the power-law fit $dN/dE \sim E^{-\Gamma}$. The dashed line illustrates typical spectra of phenomenological MSSM DM annihilation for best fit neutralino masses of 14 TeV. The dotted line shows the distribution predicted for KK DM with a mass of 5 TeV. The solid line gives the spectrum of a 10 TeV DM particle annihilating into $\tau^{+}\tau^{-}$ (30%) and $b\bar{b}$ (70%).

FIG. 1: (Color online) Background-subtracted distribution of the angle $\theta$ between the $\gamma$-ray direction and the position of Sgr A*. Circles: all detected $\gamma$-rays events. Open triangles: central object after subtraction of the $\gamma$-ray diffuse emission model (see text). Line: calculated PSF normalized to the number of $\gamma$-rays within 0.1° after subtraction is also shown. The distribution of events after subtraction matches the calculated PSF while the initial distribution shows a significant tail. The variation of the PSF related to the source energy spectrum, zenith angle and offset position in the field of view are taken into account. Insert: same distribution for the point-like source PKS 2155-304 [35]. The calculated PSF (line) also matches the data.
Pulsar wind nebula MSH15-52

CANGAROO-I.:

H.E.S.S.:
Vela X nebula

Pulsar pointing (2004 Jan/Feb)
• Stereo (T2 & T3 wobble)
• 1,311 min.
• Fisher discriminant

$\theta^2$ from Vela X center


Pulsar Wind Nebulae

Pulsar Wind Nebulae (Roberts 2006)

(Hatched: observable from Woomera)
Pulsar binary PSR 1259-63/SS2883 (1)

3.4 year highly eccentric orbit around $\sim 10 \, M_\odot$
Be star closest approach $\sim 10^{13} \text{ cm}$
or $\sim 20$ stellar radii

(i) aligned disc to the orbital plane and interaction throughout the orbit

(ii) mis-aligned disc and interaction in the $\sim 200$-day period around periastron ($\tau$), during which the radio emission is depolarized

(iii) mis-aligned disc and interaction in two short periods, $[(\tau - 18 \, \text{d}) \sim (\tau - 8 \, \text{d})]$ and $[(\tau + 12 \, \text{d}) \sim (\tau + 22 \, \text{d})]$

Pulsar binary PSR 1259-63/SS2883 (2)


PSR B1259–63
H.E.S.S.

Feb. 04
X-ray binary/microquasar LS5039

- HMXB: compact 4 (?) M\(_\odot\) object in eccentric 4 day orbit around 20-30 M\(_\odot\) star
- closest approach \(\sim 10^{12}\) cm or \(\sim 2\) stellar radii
Aharonian et al., astro-ph/0607192

Fig. 4. The orbital geometry (Casares et al. 2005) viewed from directly above LS 5039. Shown are: phases (\( \phi \)) of minimum (periastron) and maximum (apastron) separation between the two components; epochs of superior and inferior conjunctions of the compact object representing phases of co-alignment along our line-of-sight of the compact object and stellar companion. The orbit is actually inclined at an angle 13° < \( i \) < 64° with respect to the view above. VHE \( \gamma \)-rays (straight black lines with arrows) can be absorbed by optical photons of energy \( h\nu \), when their scattering angle \( \theta \) exceeds zero.

Fig. 5. Top: Integral \( \gamma \)-ray flux (\( F > 1 \) TeV) lightcurve (phaseogram) of LS 5039 from HESS data (2004 to 2005) on a run-by-run basis folded with the orbital ephemeris of Casares et al. (2005). Each run is \( \sim \)28 minutes. Two full phase (\( \phi \)) periods are shown for clarity. The blue solid arrows depict periastron and apastron. The thin red dashed lines represent the superior and inferior conjunctions of the compact object, and the thick red dashed line depicts the Lomb-Scargle Sine coefficients for the period giving the highest Lomb-Scargle power. This coefficient is subtracted from the light curve in Fig. III middle panel. 

\[ P_{\text{orb}} = 3.9 \text{d} \]
Fig. 1. Smoothed maps of gamma-ray excess events above 400 GeV around LSI +61 303. (A) Observations over 15.5 hours corresponding to data around periastron (i.e., between orbital phases 0.2 and 0.3). (B) Observations over 10.7 hours at orbital phase between 0.4 and 0.7. The number of events is normalized in both cases to 10.7 hours of observation. The position of the optical source LSI +61 303 (yellow cross) and the 95% confidence level contours for 3EG J0229+6151 and 3EG J0241+6103 (green contours) are also shown. The bottom right circle shows the size of the point spread function of MAGIC (1σ radius). No significant excess in the number of gamma-ray events is detected around periastron passage, whereas it shows up clearly (9.4σ statistical significance) at later orbital phases, in the location of LSI +61 303.
HEGRA TeV J2032+4130

Chandra ACIS-I

Fig. 1 Chandra ACIS-I image of the field of TeV J2032+4130. The positions of the marked sources are given in Table 1. The small square marks the centroid of TeV J2032+4130, and the circle is the estimated Gaussian 1σ extent of the TeV emission [9]. The triangle marks the brightest Chandra source in an earlier 5 ks observation of the region [9], noticeably absent from this image.

Mukerjee et al., astro-ph/0610299
What are H.E.S.S. unID sources?

- Near the Galactic plane: SNRs, pulsars?
- Hard spectra: marginally compatible with Fermi acceleration?
- Some may be identified with SNRs.
  - J1616-508, J1813-178, J1825-137
- Old SNRs? [Yamazaki et al., astro-ph/0601704]

Figure 5.9: Smoothed excess map (left) of the region surrounding HESS J1616–508 (left hand source). HESS J1614–518 is also visible in this map (right hand source), along with nearby pulsars and SNRs which were considered as counterparts (smoothing radius 0.06°). The figures on the right hand side show spectrum (top) and $\theta^2$ (bottom) plot of HESS J1616–508.
HESS J1813-178
= SNR AX J1813-178/G12.82-0.02

(a) VLA 90cm
(b) Spitzer 8μm / VLA 20cm / VLA 90cm

Less IR↔non-thermal


INTEGRAL 20-100 keV

HESS J1825-137 = PWN G18.0-0.7?


Fig. 1. Excess map of the region close to PSR B1823-13 (marked with a triangle) with uncorrelated bins. The best fit centroid of the γ-ray excess is shown with error bars. The black dotted circle shows the best fit emission region size ($\sigma_{\text{emission}}$) assuming a Gaussian brightness profile. The black contours denote the X-ray emission as detected by XMM-Newton. The 95% confidence region (dotted white line) for the position of the unidentified EGRET source 3EG J1826-1302 is also shown. The system acceptance is uniform at the 20% level in a 0.6° radius circle around HESS J1825-137.
Relation with CO/H\(\text{I}\)?

Figure 1. Multi-resolution filtered and reconstructed images of H.E.S.S. survey sources (the colour scale is arbitrary): (a) HESS J1614-518 and HESS J1616-508 (b) HESS J1640-465 (c) HESS J1813-178 (d) HESS J1825-137 (e) HESS J1837-069. Possible counterpart are also indicated. The positional confidence contours for EGRET sources are shown in dash Gray (green), ASCA sources are indicated with crosses. The SNRs are indicated as circles (red) and the molecular cloud contours are shown in white, the numbers show column intensity levels in K km s\(^{-1}\) units; the pulsars are shown as light Gray squares.

Lemiere et al., Proc. ICRC2005
Fig. 2:
TeV emission as shown in Fig. 1, together with the radio contours from Roberts et al. 1999. The TeV emission lines up with the wings of the Kookaburra (labeled K2/K3 and K4) and extends north of the pulsar wind nebula surrounding PSR J1420-6048 (K3) and west of the Rabbit. (Preliminary).

MOST 843MHz:
Old SNRs: large $F_{\text{TeV}}/F_X$

**Age ~ $10^3$ yr**
- $B \sim *10^{-100} \mu G$
- $E_{p,\text{max}} = 10^{2-3} \text{TeV}$
- $E_{e,\text{max}} \sim 10\text{TeV}$

**Age ~ $10^5$ yr**
- $B \sim 100 \mu G$
- $E_{p,\text{max}} = 10^{1-2} \text{TeV}$
- $E_{e,\text{max}} \sim 0.1 \text{TeV}$
Extragalactic sources: basics

- Active galactic nuclei
  - Blazars
    - Wide-band spectrum – nonthermal
  - Quasars – LBL (RBL) – HBL (XBL) sequence
  - Leptonic models
    - SSC or EC (External Compton)
  - Hadronic models
    - Proton-initiated cascades
- Radio galaxy,…
- Gamma-ray absorption by EBL (Extragalactic Background Radiation)
  - Infrared photon field: uncertain
- Center of galaxies
  - Accumulation of dark matter??
- Extragalactic background radiation
Blazars

Beaming factor

\[ \delta \equiv \frac{1}{\Gamma} (1 - \beta \cos \theta) > 1 \]

Observed frequency

\[ \nu \propto \nu_0 \delta \]

Apparent luminosity

\[ L \propto L_0 \delta^4 \]
“Known” extragalactic sources

- **Mrk421** \((z=0.031)\)

- **Mrk501** \((z=0.034)\)
  - Large flares in 1997

- **1H1426+428** \((z=0.129)\)
  - First detection in 2001 [Horan et al. 5th Compton 2001]
  - Flares in 2001
Multiwavelength spectra of blazars

Fig. 1. Simultaneous and non-simultaneous X-ray and TeV γ-ray energy spectra of the 4 TeV blazars with measured TeV γ-ray energy spectra. The regions show the range of values that have been observed with BeppoSAX, RXTE and Cherenkov Telescopes (from [46]).
Synchrotron self-Compton model

- Synchrotron + inverse Compton model works well → $e^\pm$ origin (SSC: Synchrotron Self Compton)

One-zone SSC model
$\delta = 14$, $B = 0.14$G

Synchrotron proton blazar model (1)

Target photon, p-synch cascade, μ-synch cascade, π^0 cascade, π^± cascade

Muecke et al. APh 18, 2003
Synchrotron proton blazar model (2)

\[ \frac{dF}{dE} \propto E_p^{-2}, \delta = 10, \]
\[ B = 30G, \]
\[ \gamma_{\text{max},p} = 4 \times 10^{10}, \]
\[ L_{\text{jet}} = 9 \times 10^{44}\text{erg/s} \]

Muecke et al. APh 18, 2003
<table>
<thead>
<tr>
<th>Source</th>
<th>Redshift</th>
<th>Type</th>
<th>First detection</th>
<th>Confirmation</th>
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<tr>
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<td>FR I</td>
<td>HEGRA</td>
<td>H.E.S.S.</td>
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<td>Mrk 421</td>
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<td>BL Lac</td>
<td>Whipple</td>
<td>Many</td>
</tr>
<tr>
<td>Mrk 501</td>
<td>0.034</td>
<td>BL Lac</td>
<td>Whipple</td>
<td>Many</td>
</tr>
<tr>
<td>1ES 2344+514</td>
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<td>HEGRA</td>
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<td>1ES 1959+650</td>
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<td>7TA</td>
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<td>BL Lac</td>
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<td>H1426+428</td>
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<tr>
<td><strong>H2356-309</strong></td>
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<td>1ES 1218+304</td>
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<td>MAGIC</td>
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<tr>
<td>1ES 1101-232</td>
<td>0.186</td>
<td>BL Lac</td>
<td>H.E.S.S.</td>
<td></td>
</tr>
</tbody>
</table>

⇒ Reaching further out in redshift!
TeV gamma-ray absorption on EBL (1)

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

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

Figure 2: Mean free path for photon-photon pair production in the infrared-microwave background radiation. The curves correspond to those in Fig. 1 except that the effect of Lorentz invariance violation discussed in Section 4 is shown by the long dashed curve.
TeV gamma-ray absorption on EBL (2)

EBL Spectra


EBL resolved
Universe more transparent

Reference shape

HESS limits

lower limits from galaxy counts

upper limits

measurements
Flare of PKS 2155-304 in 2006 (1)

PKS 2155-304: 2006 outburst, VERY PRELIMINARY

- Huge flux level triggered ATel, MWL observations
- 2'-minute lightcurve binning shows doubling timescales at ≈ 5'
- Complex lightcurve with possibly substructures (to be confirmed with final analysis)
- Simultaneous RXTE, Swift, Chandra, optical observations
Flare of PKS 2155-304 in 2006 (2)

- Nearby high-frequency BL Lac (z=0.117)
- TeV flare report by H.E.S.S. in July-Aug 2006 (ATel#867)
- 1,053 min (wobble), 3-fold
- Analyzed by independent teams (ICRR, Tokai, Kyoto)

CANGAROO-III: in preparation

K. Nishijima, talk at JPS meeting, Sep. 2006
TeV gamma-ray absorption on EBL (3)

We need many samples of AGNs at various redshifts!

Redshift
BL Lac, $z > 0.25$ (possibly $>0.78$ ?)

**Fig. 2.** The energy spectrum of PG1553+113. The horizontal error bars indicate the energy bin size. The dashed line represents the best $\chi^2$ fit of a power law.

Cf. Conservative limit from non-detection of features by VLT: $z > 0.09$
Sbarufatti et al., astro-ph/0601506

⇒ Upper limit: $z < 0.74$

Confirmed by MAGIC: Albert et al., astro-ph/0606161
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.
Radio galaxy M87 (1)

Or Vir A, Giant radio galaxy, z=0.00436 or 16Mpc}
Radio galaxy M87 (2)

Time scale of a few days $\leftrightarrow$ Region size $\sim 10^{13}\text{m} \approx R_{\text{Sch}}(3\times10^9\text{M}_\odot)$ !

$\leftrightarrow$ Particle acceleration near the central black hole !
Galactic diffuse gamma-rays (1)


>90% of EGRET-detected photons are diffuse!

- Cygnus
- Vela
- Geminga/Crab

> Data $E^{-2.5}$

60% Excess

- Prediction $E^{-2.7}$

- Excess

- Diffuse gamma-ray spectrum by Hunter et al.
Galactic diffuse gamma-rays (2)

OG 2.1: Diffuse γ-ray Sources

1. Galactic Plane

- Milagro [Sinnis]
  ~ 4.5σ detection in 3 yr data set.
  Inner region:
  40-100° in longitude, ±5° in latitude

- Tibet [Ohnishi]
  Flux upper limit, consistent with Milagro detection.
Figure 1 | VHE $\gamma$-ray images of the Galactic Centre region. a, $\gamma$-ray count map; b, the same map after subtraction of the two dominant point sources, showing an extended band of gamma-ray emission. Axes are Galactic latitude ($x$) and Galactic longitude ($y$), units are degrees. The colour scale is in ‘events’ and is dimensionless. White contour lines indicate the density of molecular gas, traced by its CS emission. The position and size of the composite supernova remnant G0.9+0.1 is shown with a yellow circle. The position of Sgr A* is marked with a black star. The 95% confidence region for the positions of the two unidentified EGRET sources in the region are shown as dashed green ellipses. These smoothed and acceptance-corrected images are derived from 55 hours of data consisting of dedicated observations of Sgr A*, G0.9+0.1 and a part of the data of the HESS Galactic plane survey. The excess observed along the Galactic plane consists of ~3,500 $\gamma$-ray photons and has a statistical significance of 14.6 standard deviations. The absence of any residual emission at the position of the point-like $\gamma$-ray source G0.9+0.1 demonstrates the validity of the subtraction technique. The energy threshold of the maps is 380 GeV, owing to the tight $\gamma$-ray selection cuts applied here to improve signal/noise and angular resolution. We note that the ability of HESS to map extended $\gamma$-ray emission has been demonstrated for the shell-type supernova remnants RXJ1713.7–3946 (ref. 22) and RX J0852.0–4622 (ref. 23). The white contours are evenly spaced and show velocity integrated CS line emission from ref. 11, and have been smoothed to match the angular resolution of HESS.
Diffuse gamma-rays along the plane (2)

Figure 3 | Energy distribution of Galactic cosmic rays. γ-ray flux per unit angle in the Galactic Centre region (data points), compared with the expected flux, assuming a cosmic-ray spectrum as measured in the solar neighborhood (shaded band). The spectrum of the region $|l| < 0.8^\circ$, $|b| < 0.3^\circ$ is shown using full circles. These data can be described by a power law: $dN/dE = kE^\gamma$, with $k = (1.73 \pm 0.13_{\text{stat}} \pm 0.35_{\text{sys}}) \times 10^{-8}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and a photon index $\gamma = 2.29 \pm 0.07_{\text{stat}} \pm 0.02_{\text{sys}}$. The shaded box shows the range of expected $\pi^0$-decay fluxes from this region assuming a cosmic-ray spectrum identical to that found in the solar neighborhood and a total mass of $1.7 \times 10^7$ solar masses in the region $|l| < 0.8^\circ$, $|b| < 0.3^\circ$ estimated from CS measurements. Above 1 TeV an enhancement by a factor of 3–9 relative to this prediction is observed. Using independent mass estimates derived from submillimetre measurements, $5.3 \pm 1.0 \times 10^7$ solar masses, and from C$^{18}$O measurements, $3_{-1}^{+2} \times 10^7$ solar masses, results in enhancement factors of 4–6 and 5–13, respectively (see Supplementary Information). The strongest emission away from the bright central source HESS J1745–290 occurs close to the Sgr B complex of giant molecular clouds. In a box covering this region ($0.3^\circ < l < 0.8^\circ$, $-0.3^\circ < b < 0.2^\circ$), integrated CS emission suggests a molecular target mass of $6 \times 10^6$ solar masses. The energy spectrum of this region is shown using open circles. The measured γ-ray flux (1 TeV) implies a high-energy cosmic-ray density which is 4–10 times higher than the local value. Standard γ-ray selection cuts are applied here, yielding a spectral analysis threshold of 170 GeV. The spectrum of the central source HESS J1745–290 is shown for comparison (using an integration radius of 0.14°). All error bars show ±1 standard deviation.
Diffuse source in Cygnus? (1)

- Crosses are EGRET sources
- Contours are EGRET diffuse model
- TeV/matter correlation good in Galactic latitude
- Brightest TeV Region
  - Coincident with 2 EGRET sources (unidentified)
  - 3EG J2016+3657
  - 3EG J2021+3716
- Analysis in progress
Diffuse source in Cygnus? (2)

(D) and (E) show significance maps of the Cygnus region [pixels in radius of 0.9° and sampled over a square grid of side width 0.25° for (E)] for data from 1997 to 2005. The vertical color bin widths are 0.69 SD and 0.42 SD for significance in (D) and (E), respectively. Two thin curves in (D) and (E) stand for the Galactic parallel b=±5°. Small-scale anisotropies (E) superposed onto the large-scale anisotropy hint at the extended gamma-ray emission.

Diffuse source in Cygnus? (3)

MILAGRO: A. Abdo, Santa Fe Workshop, May 2006
Gamma Ray Bursts

- Ground-based experiments?
  - TeV gamma-rays (afterglow)
    - MAGIC a few per year expected
  - Air shower rate
    - Tibet-III
  - Single particle rate
    - GRAND
    - ARGO-YBJ
    - Tibet-III
  - All-sky monitor
    - Ashra

- Need fast and precise GRB alerts!
Dark matter annihilation

Signal enhancement due to `cusp' structure toward the center?

“Explosive annihilation” by non-perturbative effect

Line

$Flux \ (cm^{-2} sec^{-1}) \ \Delta \Omega = 10^{-3}$

Continuum
## Source counts

<table>
<thead>
<tr>
<th>Source Type</th>
<th>2003</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar Wind Nebula (e.g. Crab, MSH 15-52 ...)</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Supernova Remnants (e.g. Cas-A, RXJ 1713 ...)</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Binary Pulsar (B1259-63)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Micro-quasar (LS 5039)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Diffuse (Cygnus region)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>AGN (e.g. Mkn 421, PKS 2155 ...)</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Unidentified</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>12</strong></td>
<td><strong>32</strong></td>
</tr>
</tbody>
</table>

* Includes likely associations of HESS unid sources.

→ Explosion in the number of VHE sources.
“Evolution” of the TeV gamma-ray sky

The VHE Sky - 2005

+ 8-15 add. sources in galactic plane.

R.Ong, rapporteur talk, ICRC2005
GeV vs TeV

“Evolution” in number of objects

“Kifune Plot”

Source count versus year
[T. Kifune]
Large area left unexplored at TeV

S. Funk, ICRC2005
Near future

Which Direction Should We Go?

- Low energy extension
  - Unopened window

- High sensitivity or high energy extension
  - More statistics

- Better time coverage
  - Transient sources

T. Yoshikoshi, Cherenkov 2005
VERITAS: VERITAS-4 by 2006

New site: Horseshoe canyon, Kitt Peak, Arizona
Smithsonian Inst. etc.

Prototype (Aug ’03)

Nov 2005: New Environmental Assessment
Oct 2006: Completion of Phase I: 4 telescope array
Then VERITAS-7 in 200X

To lower energies…
To lower energies...

**H.E.S.S.-II**

Khomas highland, Namibia (1800m a.s.l.)

The Next Step in BOTH directions: HESS-II

Very Large Cherenkov Telescope

- Lower threshold and increased energy range in stand-alone mode
- Improved sensitivity at higher energy in coincidence mode
- Turn-over of spectra for VHE sources
- Pulsars, Microquasars, ...
- Unidentified sources
- AGNs and cosmology, redshift coverage
- GRBs
- Dark matter

$\Phi \sim 28 \text{ m (600m}^2)\$

$f \sim 35 \text{ m Parabolic}$

$$E_{\text{thr}} \propto \left(\frac{A \epsilon}{B \Omega \Delta t}\right)^{-1}$$

$A$ mirror area, $\Omega$ angular size
$\epsilon$ photon detection efficiency
$B$ night-sky noise
$\Delta t$ integration window
MAGIC-II and III

Canary island (2200m a.s.l.)

To lower energies...

Design Study for a 34m telescope
astro-ph/0403180
To lower energies...

**MACE**

Hanle, North India (4200m a.s.l.): 2010?

21mφ
Midsized-telescope arrays

Many conceptual designs: for example,

\begin{itemize}
  \item **TenTen** (10km² at 10TeV)
    \begin{itemize}
      \item 30-50 telescopes
      \item 10-20 m² each, 5-10 deg FOV
      \item >250m spacing
    \end{itemize}
  
  \item **GRATIS**
    \begin{itemize}
      \item 37 x 6 m diameter telescopes
      \item moderate field of view (3.5 deg.)
      \item 0.2 deg. pixel/optical resolution
      \item small off-axis aberration design
      \item energy threshold
      \item \( \sim 20 \) \( \ldots \) 200 GeV with high QE
    \end{itemize}
\end{itemize}


Because the size of the HE-ASTRO, \( \sim 1 \) km², is much larger than the size of the Cherenkov light pool, \( \sim 10^8 \) cm², the number of telescopes required is \( > 200 \).
To wider sky coverage…

Wide-field optics

GAW (Gamma Air Watch)

- Flat, single-side lens
- Lens Diameter = 2.1 m
- Focal length = 2.5 m
- f/# = 1.2
- Field of view = ± 12 deg.

Mineo et al., NewHEGE3, 2005

ASHRA

- Optics:
  - Modified Baker-Nunn
- Components:
  - Correcting lens (1.0–1.2mφ) with 3 acrylic cut plates
  - Spherical mirror (2.2mφ) with 7 curved glass plates on adjustable tables
  - Photoelectric lens IT (0.5mφ) on focal sphere suspended with Stewart platform mechanism
  - Mount structure with steel channels for easy assembly


=> arcmin. resolution over 42deg FOV
=> Affordably cost-effective
To wider sky coverage...

Particle detector: HAWC

- 300m x 300m pond
- Wide FOV: ~2sr
- 100% duty cycle

- Build pond at extreme altitude (Tibet 4300m or Chile 5200m)
- Incorporate new design
  - Optical isolation between PMTs
  - Larger PMT spacing
  - Deeper PMT depth (in top layer)

$\sim$20M for complete detector

~60x sensitivity of Milagro – instantaneous sensitivity of Whipple over 2 sr
    Crab Nebula in 30 minutes (now 1 year)
    GRBs to redshift of $>$1 (now 0.4)
Let’s do them all!

CTA (Cherenkov Telescope Array)

CTA: Major European Project

$E_{th} \approx 10-20\,\text{GeV}$

$E_{th} \approx 50-100\,\text{GeV}$

$E_{th} \approx 1-2\,\text{TeV}$

International coordination

- Monitoring of time-variable objects (e.g. blazars)
- Multiwavelength observation campaign
An example: MAGIC & H.E.S.S. campaign on Mrk 421

- Mrk 421 had the most active known period during 2004
- MAGIC has observed this object for ~14 hours in different emission states (total significance of the detection is above 40σ)
- MAGIC and HESS first combined observation of AGN Mrk421 during December 2004
Summary

- Very high energy gamma-ray sources may contain large varieties, including both galactic and extragalactic objects.
- TeV gamma-ray astronomy is becoming an indispensable field of astronomy.
- Supernova remnants are confirmed to be very-high-energy particle accelerators: an important evidence of cosmic ray origin!
- Basic problem still remains: electron origin or proton origin?
- The “third generation” Cherenkov telescopes are working hard (and “fourth” ones are planned) – more fun!