Recent results from CANGAROO-III

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“CANGAROO”

= Collaboration of Australia and Nippon for a Gamma Ray Observatory in the Outback

Woomera, South Australia
Atmospheric Cherenkov light

Cherenkov light from gamma-ray showers
Lateral distribution & Timing distribution
Southern sky objects

We have placed first priorities on **Galactic objects**, i.e. supernova remnants and pulsar wind nebulae, since the beginning of the CANGAROO project, as the first imaging Cherenkov telescope observatory in the southern hemisphere.

(Hatched: observable from Woomera)
Why Woomera?

- 136°47’E, 31°06’S, 160m a.s.l.
- Desert area...good weather (72% clear nights)
- Far from large cities...dark sky
- Former rocket range and prohibited area...infra-structure, support and safety
- Adelaide group was operating BIGRAT...experience
CANGAROO team

- University of Adelaide
- Australian National University
- Ibaraki University
- Ibaraki Prefectural University
- Konan University
- Kyoto University
- STE Lab, Nagoya University
- National Astronomical Observatory of Japan
- Kitasato University
- Australia Telescope National Facility
- Tokai University
- ICRR, University of Tokyo
- Yamagata University
- Yamanashi Gakuin University
- Hiroshima University
Brief history of CANGAROO

- 1987: SN1987A (JANZOS collaboration in New Zealand)
- 1990: 3.8m telescope
- 1990: ICRR-Adelaide Physics agreement
- 1992: Start obs. of 3.8m tel.
- 1999: 7m telescope
- 2000: Upgrade to 10m
- 2001: U.Tokyo-U.Adelaide agreement
- 2002: Second and third 10m tel.
- 2004: Four telescope system
### CANGAROO-II results: summary

<table>
<thead>
<tr>
<th>Object</th>
<th>Signal</th>
<th>Publish</th>
<th>H.E.S.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR RX J1713.7-3946</td>
<td>○</td>
<td>Nature’02</td>
<td>○</td>
</tr>
<tr>
<td>Blazar Mrk421</td>
<td>○</td>
<td>ApJL’02</td>
<td>○</td>
</tr>
<tr>
<td>Starburst galaxy NGC253</td>
<td>○</td>
<td>A&amp;AL’03</td>
<td>↓</td>
</tr>
<tr>
<td>SNR SN1987A</td>
<td>↓</td>
<td>ApJL’03</td>
<td>↓</td>
</tr>
<tr>
<td>Galactic Center</td>
<td>○</td>
<td>ApJL’04</td>
<td>○</td>
</tr>
<tr>
<td>Pulsar binary PSR 1259-63/SS2883</td>
<td>↓</td>
<td>ApJ’04</td>
<td>○v</td>
</tr>
<tr>
<td>SNR RX J0852.0-4622 (Vela Jr.)</td>
<td>○</td>
<td>ApJL’05</td>
<td>○</td>
</tr>
</tbody>
</table>

- **Signal:** ○ detected, ↓ upper limit, v: variable

However, spectral indices differ significantly…

→ Re-observations with CANGAROO-III stereo system
CANGAROO-II & -III

CANGAROO-II

CANGAROO-III

7m (1999)

10m (2000)
CANGAROO-III: since 2004 March
Basic specifications of telescopes

- **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

Enomoto et al., Proc. ICRC 2003
CANGAROO-III electronics

Kubo et al., Proc. ICRC 2003
Monte Carlo simulation

- **GEANT 3.21 base**
  - 80 layers for atmosphere (12.9g/cm² each)
    - (<10% change even if more layers were used)
  - Particle transport down to 20MeV
  - Proprietary code to generate Cherenkov photons
    - Only photons coming to telescopes are tracked
  - Geomagnetic field of 0.520G (vert.) / 0.253G (hor., 6.8°E of S)
  - Rayleigh scattering $2970g/cm^2(\lambda/400nm)^4$
    - (+Mie scattering ~10% effect)
  - Detector parameters: reflectivity, point spread function, light guide efficiency, PMT Q.E., etc.
  - Night sky background
## History of CANGAROO-III

<table>
<thead>
<tr>
<th>Year</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
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<tr>
<td>T1</td>
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<td>6</td>
<td>3</td>
<td>3</td>
<td>11</td>
<td>12</td>
<td>3</td>
<td>12</td>
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<tr>
<td>T2</td>
<td>3</td>
<td>6</td>
<td>12</td>
<td>7</td>
<td></td>
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<td></td>
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<tr>
<td>T3</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

- **Construction**: Green circle
- **Observation start**: Red circle
- **Expansion to 10m**: Green square
- **Tuning**: Light blue arrow
- **Observation**: Orange line
- **Global trigger system, Maintenance**: Pink line

**Legend**
- **Construction**: Green circle
- **Observation start**: Red circle
- **Expansion to 10m**: Green square
- **Tuning**: Light blue arrow
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*Note: The timeline represents key events in the history of CANGAROO-III.*
Stereo observation of Cherenkov image

Angular resolution
0.25deg → 0.1 deg

Energy resolution
30% → 15%

Better S/N (no local muons)
Analysis of stereo observation

- Inconsistency with H.E.S.S results on some sources
  ⇒ New observations with CANGAROO III
  Efforts for advanced analysis procedures

- Measure more optical parameters
  - CCD measurements of spotsizes and stars

- Use muons for calibration
  - Tune Monte Carlo simulation

- Use the Crab as the standard candle
  - Flux obtained with Monte Carlo simulation is compared with those reported by other groups

- Independent teams within the collaboration are working:
  - Results, especially detections, are double-checked
Atmospheric transmission measurement

Data compatible with “Desert model” of MODTRAN4

Systematic errors under study
Unfortunate situation for the Crab

- The oldest T1 has higher energy threshold and bad efficiency for stereo observation
- Only T2/T3/T4 are used for stereo analysis
- Stereo baseline becomes short for the Crab observation at large zenith angles
Large zenith angle observation of the Crab

Higher energy threshold $\sim 1\text{TeV}$
Bad intersection accuracy

Far core
→ small angle
→ bad accuracy
γ/h separation by Fisher discriminant

- Linear combination of image parameters ($x_i$)
  
  \[ F \equiv \sum_i \alpha_i x_i \]

- Difference between signal ($\gamma$) and background (h)
  
  \[ D \equiv \langle F_\gamma \rangle - \langle F_h \rangle \]

- Determine $\alpha_i$ which maximize separation (solvable using correlation matrix)
  
  \[ S \equiv \langle D \rangle^2 / \langle (D - \langle D \rangle)^2 \rangle \]

- With calculated $\alpha_i$ for a known source, the (appropriately normalized) combination $F$ could be the “Fisher discriminant” for other sources.

- We use widths and lengths of multiple telescopes for image parameters ($x_i$).

Crab signal

- T2 & T3
- 890 min (Dec. 2003)

Crab spectrum

Differential flux (cm$^{-2}$s$^{-1}$TeV$^{-1}$)

- **CANGAROO**
  - Blue: FD
  - Red: Likelihood

**HESS** (2006)


**Excess event map**

Angular resolution ~ 0.23 deg

PSR 1706-44

- Pulsar pointing (2004 May)
- Stereo (T2, T3 & T4 long ON/OFF)
- 1,625 min. ON, 1,738 min. OFF
- T2 & T3 results on square cut
- Independent analysis (Fisher disc.)

⇒ To be checked with our latest analysis methods
SN1006 (G327.6+14.6)

- NE-rim pointing (2004 May)
- Stereo (T2, T3 & T4 long ON/OFF)
- 1,625 min. ON, 1,738 min. OFF
- T2 & T3 results on likelihood
- Independent analysis (Fisher disc.)

\[ \theta^2 \text{ from NE rim} \]

\[ \Rightarrow \text{To be checked with our latest analysis methods} \]
Vela pulsar/nebula

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

$\theta^2$ from Vela X center

Vela X nebula: spectrum

\[ \theta^2 < 0.6 \, \text{deg}^2 \]

Excess $561 \pm 114$

H.E.S.S.:
Aharonian et al.,
AA 448, L43 (2006)
\[ \propto E^{-1.45} \exp(-E/13.8 \text{TeV}) \]
CANGAROO-II claims vs. H.E.S.S.

- CANGAROO-II claims
  - **SNR RX J1713.7-3946**: 0.51Crab, $E^{-2.84 \pm 0.15 \pm 0.20}$ ($11\sigma$, $>0.5$ TeV)  
    [Enomoto et al., Nature 416, 823, 2002]  
    - Cf. H.E.S.S. flux: 0.83Crab, $E^{-2.19} \pm 0.09 \pm 0.15$  
  - **NGC253**: 0.15Crab ($11\sigma$, $>0.5$ TeV)  
    [Ito et al., A&A 402, 443, 2003]  
    - Cf. H.E.S.S. upper limit: 0.05Crab  
      [Aharonian et al. A&A 442, 177, 2005]
  - **Galactic center**: $E^{-4.6(+1.2-5.0)}$  
    - Cf. H.E.S.S. spectrum: $E^{-2.2} \pm 0.09 \pm 0.15$  
  - **SNR RX J0852.0-4622**: $E^{-4.6(+1.7-4.4)}$  
    - Cf. H.E.S.S. spectrum: $E^{-2.1} \pm 0.1\pm 0.2$  

⇒ To be checked with CANGAROO-III stereo data
SNR RX J0852.0-4622

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

Fisher discriminant

\[ \theta^2 \text{ from SNR center} \]
SNR RX J0852.0-4622: spectrum

\[ \frac{dF}{dE} = \left[ 2.5 \pm 0.6(\text{stat.}) \pm 0.6(\text{sys.}) \right] \times 10^{-11} \]

\[ \cdot \left( \frac{E}{1 \text{ TeV}} \right)^{2.2 \pm 0.3(\text{stat.}) \pm 0.3(\text{sys.})} \]

\[ \text{[cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}] \]

**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.

Comparison with C-II
Starburst galaxy NGC253

- 3-fold, 2004 Oct, 1179min (ON), 753min (OFF)

Fig. 3. Excess count map. The rainbow map is the excess count. The black contour is DSS2 (second version of Digital Sky Survey) data. The dotted circle is 0.5 degree radius. The point spread function is shown in left-below corner (the dashed line).

Fig. 4. Integral fluxes. The points with error bars are the CANGAROO-II’s ones (see text for the detail). The black curve is 99% upper limit (UL) by H.E.S.S. for point source assumption. The green is that for 0.5 degree diffuse source. The red is 2σ UL for this observation for point source assumption and the blue for 0.5 degree diffuse.
Flare of Blazar PKS 2155-304

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

\[ \theta^2 \text{ distribution} \]

\[ \text{Fisher discriminant} \]

\[ \text{Day by day lightcurve} \]
Summary of TeV source status claimed by CANGAROO compared with H.E.S.S results

<table>
<thead>
<tr>
<th>Object</th>
<th>C-I</th>
<th>C-II</th>
<th>C-III</th>
<th>H.E.S.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes [2]</td>
<td>Yes</td>
</tr>
<tr>
<td>Vela pulsar</td>
<td>Yes (0.13° offset)</td>
<td>N/A</td>
<td>U.L.  [2]</td>
<td>U.L.</td>
</tr>
<tr>
<td>Vela X</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes [2]</td>
<td>Yes</td>
</tr>
<tr>
<td>SN1006</td>
<td>Yes†</td>
<td>U.L.  [1]</td>
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<td>U.L.</td>
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<tr>
<td>RX J1713.7-3946</td>
<td>Yes</td>
<td>Yes under analysis</td>
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<td>Yes</td>
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<tr>
<td>PSR 1509-58</td>
<td>Yes</td>
<td>N/A</td>
<td>under analysis</td>
<td>Yes (MSH15-52)</td>
</tr>
<tr>
<td>Mrk 421</td>
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<tr>
<td>Galactic center</td>
<td>N/A</td>
<td>Yes under analysis</td>
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<tr>
<td>RX J0852.0-4622</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes [3]</td>
<td>Yes</td>
</tr>
</tbody>
</table>

‘C-I’ means CANGAROO-I, etc. ‘Yes’: detection, ‘U.L.’: upper limit, ‘N/A’: not available. † means the result is not published yet.


[2] “A Search for sub-TeV Gamma-rays from the Vela Pulsar Region with CANGAROO-III”


Up and coming sources…

- MSH 15-52
  - Pulsar wind nebula (PSR 1509-58)
  - H.E.S.S.: 25% Crab, extended (~6’x2’)
  - Observation: 40hr in 2005, 90hr in 2006

- HESS J1804-216
  - G8.7-0.1(SNR) / PSR J1803-2137
  - H.E.S.S.: 25% Crab, extended (~12’)
  - Observation: 90hr in 2006

- HESS J1303-631
  - Unidentified
  - H.E.S.S.: 17% Crab, extended (~10’)
  - Observation: 70hr in 2006

- Cen A
  - Radio galaxy (z=0.0018)
  - H.E.S.S.: upper limit (2% Crab)
  - Observation: 20hr in 2004

- And more…
Summary

- CANGAROO-III atmospheric Cherenkov telescope system are observing sub-TeV gamma-rays since 2004 March in stereoscopic mode.

- Observations of SN1006 and PSR1706-44 were made by using CANGAROO-III telescopes. Preliminary analyses appear to show no significant signals, yielding upper limits lower than the CANGAROO-I fluxes obtained several years ago.

- Observation of Vela pulsar showed no gamma-ray signal, but there is a hint of signal in the Vela X nebula.

- SNR RX J0852.0-4622 was detected as an extended source, and the morphology seems to follow the X-ray emission profile.

- Starburst galaxy NGC 253 was observed with CANGAROO-III but the signal reported by CANGAROO-II was not confirmed.

- A flaring activity of a blazar PKS 2155-304 was detected in July-August 2006 showing rapid time variation.

- Analysis of stereo observations are now established, and application to other sources are underway.