CANGAROO Project for High-Energy Gamma-ray Astrophysics

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

Observation of high-energy gamma-rays from celestial objects with imaging atmospheric Cherenkov telescopes in Woomera, Australia

Woomera, South Australia
## CANGAROO team

- University of Adelaide
- Australian National University
- Ibaraki University
- Ibaraki Prefectual University
- Kanagawa University
- Konan University
- Kyoto University
- Nagoya University
- National Astronomical Observatory of Japan
- Osaka city University
- Institute of Physical and Chemical Research
- Shinshu University
- Institute for Space and Aeronautical Science
- Tokai University
- Tokyo Institute of Technology
- Yamagata University
- Yamanashi Gakuin University
Multiwavelength astronomy

**Radio Continuum**
- 408 MHz Bonn, Jodrell Banks, & Parkes

**Atomic Hydrogen**
- 21 cm Leiden-Dwingeloo, Maryland-Parkes

**Radio Continuum**
- 2.4-2.7 GHz Bonn & Parkes

**Molecular Hydrogen**
- 115 GHz Columbia-GISS

**Infrared**
- 12, 60, 100 μm IRAS

**Near Infrared**
- 1.25, 2.2, 3.5 μm COBE/DIRBE

**Optical**
- Laustsen et al. Photomosaic

**X-Ray**
- 0.25, 0.75, 1.5 keV ROSAT/PSPC

**Gamma Ray**
- >100 MeV CGRO/EGRET
New window on Universe

Energy flux

- Thermal radiation
- Nonthermal radiation - power-law spectrum -
  - Gamma Rays
  - Cosmic Rays
- Satellite
- Ground Based Gamma Ray obs.

- Log E (eV)
- Conventional window ↔ New window through gamma-rays

©T. Kifune
Gamma-ray emission: non-thermal

- High energy electron + magnetic field
- High energy electron + atomic electric field
- High energy proton + matter
- High energy electron + photon field

**Synchrotron Radiation**
- Magnetic-field lines
- Gamma ray
- Electron

**Meson Decay**
1. Proton hits nucleus
2. Meson produced
3. Meson decays into gamma rays

**Bremsstrahlung**
- Positively charged nucleus
- Gamma ray
- Electron

**Inverse Compton Scattering**
- Fast moving electron
- Low-energy photons
- High-energy gamma ray

High energy particles ↔ particle acceleration process
Gamma-ray sky (1)

EGRET All-Sky Gamma Ray Survey Above 100 MeV
Gamma-ray sky (2)
<table>
<thead>
<tr>
<th>Source Description</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsars</td>
<td>5</td>
</tr>
<tr>
<td>AGN (mostly blazars)</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>27 (marginal)</td>
</tr>
<tr>
<td>Radio galaxy (Cen A)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1 (marginal)</td>
</tr>
<tr>
<td>Unidentified (Some may be SNRs)</td>
<td>170</td>
</tr>
<tr>
<td>Large Magellanic Cloud</td>
<td>1</td>
</tr>
<tr>
<td>Solar flare</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>271</strong></td>
</tr>
</tbody>
</table>
Detection of gamma-rays
Cherenkov telescope

- Cherenkov angle

\[
\cos \theta = \frac{1}{n\beta}
\]

\[
\beta = \frac{v}{c}
\]

\[
n = 1.0003 \text{ (1 atm)}
\]

\[\Rightarrow \theta = 1.3^\circ\]
Discrimination of cosmic-ray background (1)

100 GeV gamma-ray

300 GeV proton
Discrimination of cosmic-ray background (2)

Gamma-ray:
Electromagnetic shower
⇒ Sharp image

Proton:
Nuclear shower
⇒ Diffuse image
Discrimination of cosmic-ray background (3)

Due to perspective, images of individual air showers appear elongated unless seen head-on. Those originating from a common point \((A, B, C)\) reveal a distinct source of gamma rays; those with random orientation \((D, E)\) presumably stem from the cosmic-ray background.
Discrimination of cosmic-ray background (4)


(Simulation)
The first TeV source: Crab Nebula

Whipple 10m telescope (Arizona, USA)


In 1986 the familiar Crab Nebula provided Whipple Observatory astronomers with their first point-source TeV detection. Each count in this Whipple TeV "image" of the Crab represents the intersection of coincident, elliptical images like those depicted on page 24. The image's large angular extent is an artifact of the telescope's limited resolution. Courtesy John Quinn. Inset: This three-color visible-light composite of the Crab was obtained on California's Mount Pinos by Bill and Sally Fletcher.
TeV gamma-ray sky in 2002

TeV Gamma-ray Sources

- Purple shade: field-of-view of Whipple
- Blue shade: field-of-view of CANGAROO

- Grade A
- Grade B
- Grade C
<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
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</thead>
<tbody>
<tr>
<td>4 Pulsar nebulae</td>
<td>Crab, Vela, PSR 1706-44, PSR1509-58</td>
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<tr>
<td>8 Blazars</td>
<td>Mrk 421, Mrk 501, 1ES2344+514, PKS 2155-304, 3C66A, BL Lac, 1H1426+428, 1ES1959+65</td>
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<tr>
<td>3 Supernova remnants</td>
<td>SN1006, Cas A, RX J1713.7-3946</td>
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<tr>
<td>1 X-ray Binary</td>
<td>Cen X-3</td>
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<tr>
<td>1 Starburst galaxy</td>
<td>NGC253</td>
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</table>
Pulsar nebulae

- Fast rotating magnetized pulsar = power generator
- E.M. energy ⇒ Pulsar wind out of light cylinder
- Shock wave in ambient medium ⇒ particle acceleration
- Gamma-rays by IC
Energy spectrum of Crab

Unpulsed

Pulsed


D. Thompson, 4th Compton Symp. 1997
Blazars

- Matter accretion to massive black hole $\Rightarrow$ release of gravitational energy
- High speed jet ejection from B.H.
- Shock wave in jets $\Rightarrow$ particle acceleration
- Gamma-rays from IC or proton-induced cascade
Blazar spectrum

- Double-peaked structure
  = synchrotron + inverse Compton
  (Synchrotron Self Compton model)

Supernova remnants

- Expanding blast wave from explosion ⇒ shock wave
- Particles accelerated in shock wave
- Interaction with ambient medium
  - $e + \hat{B}$ (syncrotron)
  - $e +$ Photons (IC)
  - $p +$ Gas ($\pi^0$)
  ⇒ Gamma-rays
- Cosmic ray origin? (energetics argument)
Brief history of CANGAROO

- 1987: SN1987A
- 1990: 3.8m telescope
- 1990: ICRR-Adelaide Physics agreement
- 1992: Start obs. of 3.8m tel.
- 1994: PSR 1706-44
- 1998: SNR1006
- 1999: 7m telescope
- 2000: Upgrade to 10m
- 2001: U.Tokyo-U.Adeelaide agreement
- 2002: Second and third 10m tel.
JANZOS project in New Zealand

Japan Australia New Zealand
Observation of Supernova 1987A

Shower particle detector array + Three Fixed Cherenkov telescopes
Why Woomera?

- NZ: too wet, not many clear nights
- Woomera:
  - Former rocket range and prohibited area...infrastructure and support
  - Adelaida group was operating BIGRAT

ELDO rocket Launch site in '60s

BIGNAT (B1centinnial Gamma RAy Telescope)
3.8m telescope: ex. Lunar ranging

Imaging camera at the prime focus

Tadashi Kifune & John Patterson
PSR 1706-44: the first southern TeV object

- 102ms pulsar
- Age: 17,000 yr
- GeV gamma-ray source (pulsed)
- TeV emission confirmed by Durham group and CANGAROO 7/10m
- Emission mechanism: still unclear

Significance map near PSR:
(Left: ON, Right: OFF)

Supernova remnant 1006 (1)

- Historical SNR recorded in 1006
- Nonthermal X-rays detected by ASCA (Koyama et al. 1995) ⇒ *Synchrotron* emission by high energy electrons
- Inverse Compton emission expected and detected by CANGAROO!

Supernova remnant 1006 (2)

Well fit by inverse Compton emission from electrons

⇒ SNR as a high-energy accelerator!
CANGAROO-II: 7m telescope

- Completed in 1999
- 60 x 80cm CFRP mirror segments
- Focal length 8m
- 512ch imaging camera
- Fast electronics (charge and timing)
CANGAROO-III: Stereo imaging

- 4 x 10m telescopes to be completed in 2003

![Diagram of telescopes and CANGAROO-II and III setups]
Stereo imaging of Cherenkov light

- Cherenkov shower pool: \( \sim 300 \text{m} \phi \)
- Stereo \( \Rightarrow \) Info. on distance to showers
- Better angular resolution
- Better energy resolution
Construction of 2\textsuperscript{nd} 10m telescope in 2002
Present status: Three 10m telescopes in Woomera

T2
Started operation in Dec. 2002

T3
Assembled in Dec. 2002

T1
In operation since 2000
SNR RX J1713.7-3946

- SNR detected by X-ray satellite
- Non-thermal emission

Gamma-ray signal = (OFF) – (ON)

Energy spectrum

Eonomoto et al. Nature 2002
SNR RX J1713.7-3946: emission from protons?

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

⇒ Emission from protons ($\pi^0$)?

⇒ Cosmic ray origin?

Enomoto et al. Nature 2002
Systematic study of SNRs

- Crab nebula ("Standard candle")
- Vela (CANGAROO)
- RX J1713.7-3946 (CANGAROO)
- Cas A (HEGRA)
- RCW86 (CANGAROO under analysis)
- RX J0852-46 (CANGAROO under analysis)

Instruments used:
- Chandra
- ASCA
- ROSAT
Blazar: Markarian 421

- The first TeV AGN in the northern sky
- $z=0.031$ ($\sim 130\text{Mpc}$)
- Flare in 2001
- Large zenith angle observation from Woomera: higher energy
- Intergalactic absorption by IR: No 10TeV photons?

Gamma-ray signal = (OFF) – (ON)

Optical image

Mrk 421: hint for cosmology?

Emission above 10 TeV detected
⇒ Fewer IR photons?
⇒ Cosmology: galaxy formation

TeV gamma-ray absorption by IR background

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

Summary of extragalactic background light measurements

Mean free path for \( e^+e^- \) pair production

Figure 5: Summary of extragalactic background light (EBL) measurements and limits. Error bars for detections are 1\sigma. Square symbols show upper limits obtained by integrating the light of detected sources. X’s show 2\sigma lower limits on integrated resolved sources from Bernstein (1998). Diamonds show upper limits from fluctuation measurements. All other symbols show absolute background measurements (1\sigma error bars) or limits (2\sigma). The shaded region represents current observational limits for the EBL spectrum, and the dotted line shows nominal values (see §3.10 for discussion). The black line (CMB) shows the cosmic microwave background radiation.

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.
Starburst galaxy NGC 253

- Nearby spiral galaxy (2.4Mpc)
- Starburst activity ⇔ frequent SNe

Gamma-ray signal = (OFF) – (ON)

Optical image

Itoh et al. A&AL 2002
Cherenkov telescopes in the world

TELESCOPE

Pedestal

Overall Optical Support Structure
Accommodates 12m mirror
Satellites waiting for launch

AGILE (ASI [Italy] 2003)

GLAST (NASA, 2006)
Near future
GeV Gamma-ray sky in 2007?

5σ Sources from Simulated One Year All-sky Survey

Results of one-year all-sky survey. (Total: 9900 sources)

AGN
3EG Catalog
Galactic Halo
Galactic Plane

LAT 1st Catalog: >9000 sources possible
Number of sources vs. year

“Kifune Plot”

Log scale!
Summary

- Gamma-ray astronomy – last frontier of astronomy
- Gamma-rays are emitted by non-thermal particle acceleration process
- TeV astronomy emerged in late ’80s is rapidly growing
- CANGAROO is a pioneer of Southern TeV sky
- Non-thermal universe will be explored deeply in near future