超高エネルギーガンマ線による天体物理

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極限エネルギーガンマ線と宇宙線による宇宙像」
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Detection of gamma-rays (1)

TeV Gamma-ray

MeV-GeV Gamma-ray

Cherenkov light

Air shower

Satellite

Atmosphere

Cherenkov telescope

> TeV gamma-rays

air shower
Atmospheric Cherenkov telescopes

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

Shower profile
- Gamma (100 GeV)
  - Regular
- Proton (300 GeV)
  - Irregular

Focal plane image
- Gamma
  - Sharp
- Proton
  - Diffuse

Image parameters of a shower
- Length
- Width

Field of view of a telescope (about 3 degrees)

$\alpha$ (image orientation angle)
## 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 Cherenkov)</td>
<td>Indirect (shower array)</td>
</tr>
<tr>
<td>Energy</td>
<td>$&lt; 30 \text{ GeV}$ ($\rightarrow 100 \text{ GeV}$)</td>
<td>$&gt;100 \text{ GeV}$ ($\rightarrow 50 \text{ GeV}$)</td>
<td>$&gt;3 \text{ TeV}$ ($\rightarrow 1 \text{ TeV}$)</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>(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>
Imaging Cherenkov telescopes in operation

HEGRA-CT
Germany etc.
3m $\phi \times 5$
(2200m a.s.l.)
(closed)

Whipple
USA etc.
10m $\phi$
(2200m a.s.l.)

CANGAROO
Japan/Australia
10m $\phi$
(1600m a.s.l.)

CAT
France etc.
5m $\phi$
(1600m a.s.l.)
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 10 GeV: pulsed+unpulsed
    - Above: unpulsed only
    - Unpulsed: SSC (Synchrotron-Self-Compton) model
    - Where is the cutoff?
    - (Pulsar emission models)
  - Others? Vela, PSR1706-44,…
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 2000

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

Integral gamma-ray flux at the distance $d = 1$ kpc

- $B = 5 \mu G$, ejecta $v$-distribution
- $\eta = 10^{-3}$
- $\eta = 10^{-4}$
- DAV (mean ejecta speed)
- $t_{\text{sweep}} = t_0$

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: $\pi^0$
Dot-dash: brems
(Data: EGRET IC443)
Pulsar nebula

- 周囲のガス圧とバランスするとそこで衝撃波が形成され、圧縮加熱されたパルサー風がシンクロトロン放射で輝く

K. Mori, talk at ICRR, Dec 2003
The Crab

Inner ring = Shock front

Optical + X-ray image

Asahara et al., SPIE 2002

Crab (pulsed)

Crab (unpulsed)

Synchrotron Self Compton
“Known” galactic sources

- Crab “The standard candle”
  - Well established (many observations since 1989)
- Pulsar PSR 1706-44
  - CANGAROO 1995
- Vela pulsar
  - CANGAROO 1997
- Supernova remnant SN1006
  - CANGAROO 1998, HEGRA CT1 2003
- Supernova remnant RX J1713.7-3946
  - CANGAROO 2000, 2002
- Supernova remnant Cas A
  - HEGRA CT system 2001
SN 1006 emission mechanism

Naito et al. AN 320 (1999)

Voelk et al. AA 396 (2002)
SN 1006: HEGRA CT1

- HEGRA CT1
- 219hrs
- >18TeV
- 5σ excess
- Position within 0.1° of CANGAROO hotspot

Vitale et al. 28th ICRC (2003)
SN 1006: H.E.S.S.

CT3 Observations:
4.5 hrs livetime
14 On/Off pairs after quality selection

2-D excess:
1.0 $\sigma$

Background after cuts
0.96 min.$^{-1}$

Cangaroo hotspot marked by circle

Excess as function of distance from Cangaroo hotspot

Conor Masterson, H.E.S.S.

28th ICRC Tsukuba 2003

Masterson et al., 28th ICRC (2003)
SNR RX J1713.7-3946 (1)

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

Gamma-ray signal = (ON) – (OFF)

Significance map

Energy spectrum

Hard to explain by emission from electrons (Brems, IC) ⇒ Emission from protons ($\pi^0$)? ⇒ Cosmic ray origin?

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

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

Counter arguments

* Butt et al., Nature 418 (2002) 489
SNR Cas A

Gamma-ray signal = (ON) – (OFF)

HEGRA-CT system (stereo)
232 hrs

More TeV SNRs?

Ueno, talk in Kyoto, Dec 2003
Systematic study of SNRs

- Crab nebula
- Vela
- RX J1713.7-3946
- SN1006
- RCW86
- RX J0852-46

Supernova Remnants (Green 1996)

- ASCA
- ROSAT
- Chandra
- Optical
New entry: \textbf{TeV J2032+4130}

- \textbf{Unidentified TeV source TeV J2032+4130}
  - Very hard spectrum $E^{-1.9}$
  - No counterpart in radio or X-rays

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\begin{itemize}
  \item \textbf{Location (J2000.0)}
  \hspace{1cm}
  \begin{align*}
    \alpha_0 & : 20^\text{hr} 31^\text{m} 57^s & \pm 6.2_{\text{stat}}^{+13.7}_{\text{sys}} \\
    \delta_0 & : 41^\circ 29' 57'' & \pm 1.1_{\text{stat}}^{+1.0}_{\text{sys}}
  \end{align*}

  \rightarrow \text{TeV J2032+4130}

\end{itemize}

\begin{itemize}
  \item \textbf{Source Stats.}
    \hspace{1cm}
    \begin{align*}
      \text{Excess} & : 252 \text{ events} \\
      \text{Significance} & : 0.9 \gamma \text{ h}^{-1} \\
      \text{Source Extension} & : 6.2' \pm 1.2_{\text{stat}}^{+0.9}_{\text{sys}} \\
    \end{align*}

\end{itemize}

Rowell et al., 28\textsuperscript{th} ICRC (2003)
New entry: SNR RX J0852.0-4622

- CANGAROO 10m result

Vela SNR

$\sim 8^\circ$

$\sim 1\text{kpc}$

Maximum X-ray emission

Number of events per $5^\circ$

5.3$\sigma$ excess

Gamma-ray signal (ON-OFF)

Preliminary!

Katagiri et al., 28th ICRC (2003)
New entry: Galactic center

- CANGAROO 10m result

Gamma-ray signal (ON-OFF)

Tsuchiya et al., 28th ICRC (2003)
Galactic plane survey

Spatial pattern: source population along the Galactic plane?

HEGRA CT system

16.2 hrs
4.5 σ

5.3 hrs
4.2 σ

70.5 hrs
4.6 σ

TeVJ1915.2+11.47

Puehlhofer et al., 28th ICRC (2003)
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
\[ \delta = \frac{1}{\Gamma (1-\beta \cos \theta)} > 1 \]

Observed frequency
\[ v \propto v_0 \delta \]

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

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

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

- **1H 1426+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

$\Gamma = 14$, $B = 0.14$G

Synchrotron proton blazar model (1)

Muecke et al. APh 18, 2003
$dF/dE \propto E^{p-2}, \delta = 10, B = 30\text{G}, \gamma_{\text{max},p} = 4 \times 10^{10}, L_{\text{jet}} = 9 \times 10^{44}\text{erg/s}$

Muecke et al. APh 18, 2003
Mrk421: Whipple Flare Dec02-Jan03

Correlated flare

Correlation is not simple!

"Orphan" X-ray flare

Rebillot et al. 28th ICRC (2003)
Mrk421: Whipple  Hourly variability


Harder for stronger  ⇔  Constant slope

Why this difference?

Krennrich et al., 28th ICRC (2003)
TeV gamma-ray absorption on EBL (1)

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

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

Dwek, "Universe Viewed in Gamma-rays", Kashiwa, 2002

Protheroe et al. astro-ph/0005349

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)

H1426+428: HEGRA CT system

$z = 0.129$

EBL (Extragalactic Background Light)

Horns et al., 28th ICRC (2003)
Confirmed extragalactic sources

- **1ES1959+650** (Blazar, $z=0.048$)
  - Utah 7TA detection [Nishiyama et al. 1999ICRC] 3.9σ
  - Large Flare in 2002
    - HEGRA CT system [Aharonian et al. 2003A&A]
    - HEGRA CT1 [Tonello et al. 28th ICRC 2003]
    - Whipple [Holder 2019]

- **1ES2344+514** (Blazar, $z=0.044$)
  - HEGRA CT system [Tluczykont et al. 28th ICRC 2003] 4.4σ

- **PKS2155-304** (Blazar, $z=0.116$)
Fig. 1. The Whipple (top) and RXTE (bottom) light curves for 1ES1959+650 in May-July 2002. The filled Whipple points correspond to $> 3 \sigma$ detections. The RXTE data are from [6].
PKS 2155-304

- H.E.S.S. (single telescope)

**Fig. 1.** The pointing angle α-plot of PKS 2155-304 observations for July (left panel) and October (right panel) 2002. The OFF-source distributions have been normalised to the control region between 30° and 90°.

<table>
<thead>
<tr>
<th>PKS2155</th>
<th>$T_{\text{live}}$ (h)</th>
<th>Non</th>
<th>Noff</th>
<th>Excess</th>
<th>$\gamma$/min</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul 2002</td>
<td>2.2 h</td>
<td>1029</td>
<td>625</td>
<td>404</td>
<td>3.1</td>
<td>9.9 σ</td>
</tr>
<tr>
<td>Oct 2002</td>
<td>4.7</td>
<td>1444</td>
<td>1107</td>
<td>337</td>
<td>1.2</td>
<td>6.6 σ</td>
</tr>
</tbody>
</table>
TeV blazar population?
New entry: NGC253 (1)

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

Gamma-ray signal = (ON) – (OFF)

Optical image

Itoh et al.
A&AL (2002)
New entry: NGC253 (2)

- Extended halo?

Significance map by CANGAROO

New entry: M87 (1)

- M87 (Vir A, Giant radio galaxy, \(z=0.00436\) or 16Mpc)
  - HEGRA CT system detection
  - Whipple upper limit

AGN \(~10^9M_\odot\) B.H.

Jet

Optical image
New entry: M87 (2)

- M87: HEGRA CT system 1998-1999 4.4σ

Goetting et al. 28th ICRC (2003)
New entry: M87 (3)

- **M87: Whipple** 2000-2001 2.4σ, 2002-2003 no excess

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**Fig. 1.** The Whipple 10-m upper limit on the differential flux from M87 compared to the detection by HEGRA under the assumption that the spectrum can be described by a power law of index 2.5.

LeBohec et al., 28th ICRC (2003)
M87 models

- Inverse Compton by electrons  

- Misaligned ‘synchrotron proton blazar’ model

Reimer 2003 ICRC
Galactic diffuse gamma-rays (1)


![Diffuse gamma-ray spectrum by Hunter et al.](image)

- Data $E^{-2.5}$
- Prediction $E^{-2.7}$
- 60% Excess
Galactic diffuse gamma-rays (2)

Summary by Mori, ICRC2003
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

- **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

Continuum

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

Hisano, Matsumoto, Nojiri PRL 92 (2004)
“Evolution” of the TeV gamma-ray sky
“Evolution” in number of objects

Log scale

Number of sources vs time

Year


X-rays

γ-rays

EGRET

COS B

SAS-2

VHE γ-rays

ICRC2003

“Kifune plot”

©Rene Ong 2002
New Cherenkov telescopes

The “Big Four”
CANGAROO-III: completion in 2003

Four 10m telescopes (3 completed) in Woomera, Australia
ICRR, Univ.Tokyo, Kyoto Univ., Univ. Adelaide etc.
H.E.S.S.: completion in 2003

Dec. 10: All four H.E.S.S. telescopes operational!

Four 12m telescopes (2 completed) in Namibia, Africa
Max Planck Inst., Heidelberg, etc.
MAGIC: completion in 2003

One 17m telescope in Canary Island
Max Planck Inst., Munich, etc.
VERITAS: VERITAS-4 by 2005, then -7

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

Prototype (Aug ’03)

Oct 2005: Completion of Phase I:
4 telescope array

Oct 2007: Completion of Phase II:
7 telescope array
International coordination

- Monitoring of time-variable objects (e.g. blazars)
- Multiwavelength observation campaign
Summary

- Very high energy sources may contain large varieties, including both galactic and extragalactic objects.
- TeV gamma-ray astronomy is becoming an indispensable field of astronomy.
- The “third generation” Cherenkov telescopes are about to increase sensitivity — more fun!