TeVガンマ線による
天体物理

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高エネルギー宇宙の総合的解読  宇宙線研究所、March 8-9, 2004
天体ガンマ線の検出法

<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 GeV (→ 100 GeV)</td>
<td>&gt;100 GeV (→ 50 GeV)</td>
<td>&gt;3 TeV (→ 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 Δθ</td>
<td>Large FOV</td>
</tr>
<tr>
<td>Cons</td>
<td>Small area</td>
<td>Low S/ N (CR bkgd.) (but imaging overcomes this)</td>
<td>Low S/ N (CR bkgd.) Moderate Δθ</td>
</tr>
<tr>
<td></td>
<td>High cost</td>
<td>Small FOV</td>
<td></td>
</tr>
</tbody>
</table>
“CANGAROO”

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

大気チェレンコフ望遠鏡による TeV領域天体ガンマ線の 地上観測
CANGAROO
CANGAROOチーム(日豪共同)

- University of Adelaide
- Australian National University
- Ibaraki University
- Ibaraki Prefectual University
- Kitasato University
- Konan University
- Kyoto University
- Nagoya University
- National Astronomical Observatory of Japan
- Osaka City University
- Shinshu University
- Institute for Space and Aeronautical Science
- Tokai University
- ICRR, University of Tokyo
- Tokyo Institute of Technology
- Yamagata University
- Yamanashi Gakuin University
銀河系内のガンマ線源

■ 超新星残骸 ＝ 宇宙線の起源？
  ■ エネルギー収支 － OK (if 10% of $E_{SN}$ goes to CR)
  ■ 最大加速エネルギー － “Knee”領域まで
  ■ 何個あるか？
  ■ 高エネルギー電子の存在は確実だが、高エネルギー陽子の証拠はどうか？

■ パルサーとパルサー星雲 (plerions)
  ■ かに星雲 － “The standard candle”
    ■ Up to a few 10GeV: pulsed+unpulsed
    ■ Above: unpulsed only
    ■ - Unpulsed: SSC (Synchrotron-Self-Compton) model
    ■ - エネルギーのカットオフ？
    ■ - (Pulsar emission models)
  ■ Others? Vela, PSR1706-44,…
超新星残骸

- 超新星爆発による拡大する爆風 ⇒ 衝撃波
- 衝撃波による粒子加速
- 周囲の物質との相互作用
  - e + B (シンクロトロン)
  - e + 光子 (IC)
  - p + 物質 (π^0)
  ⇒ ガンマ線放射
- 宇宙線の起源？
  (エネルギー学に基づく古くからの議論)

Cas A (X線画像)
Particle acceleration in SNR

Non-linear kinetic theory

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

Particle spectrum

Maximum momentum

Berezhko & Voelk, APh 1997

Fig. 2. The maximum CR momentum as a function of time for the same cases as in Fig. 1.

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

$B = 30 \mu G$

$\eta = 10^{-3}$

$\eta = 10^{-4}$

DAV (mean ejecta speed)

$t_{\text{sweep}} = t_0$

1000-10000 yr
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: π$^0$
Dot-dash: brems
(Data: EGRET IC443)
周囲のガス圧とバランスするとこ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
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

- 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**

Electron origin vs Proton origin

SN 1006 rim structure

Chandra image

Black: efficient proton acceleration $\epsilon_p = 0.0015$
Green: inefficient $\epsilon_p = 0.04$

SN1006: HEGRA CT1

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

Gamma-ray signal = (ON) – (OFF)

Vitale et al. 28th ICRC (2003)
**SN 1006 CT3**

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
SNR RX J1713.7-3946 (1)

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

Energy spectrum

Significance map

Gamma-ray signal = (ON) – (OFF)

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

⇒ Emission from protons ($\pi^0$)?

⇒ Cosmic ray origin?

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

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

Counter arguments

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

Gamma-ray signal = (ON) – (OFF)

HEGRA-CT system (stereo)

232 hrs

Cas A: proton accelerator?

Berezhko et al., AA 400 (2003)
## Comparison of SNRs

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance (kpc)</th>
<th>Age (yr)</th>
<th>Density (cm(^3))</th>
<th>Mag. field (G)</th>
<th>SN type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN1006</td>
<td>2.2</td>
<td>1000</td>
<td>0.1-0.3</td>
<td>Several (\mu) (\rightarrow 120 (\mu))</td>
<td>Ia</td>
</tr>
<tr>
<td>RX J1713.7-3946</td>
<td>1</td>
<td>1600(?)</td>
<td>0.01(amb)-10(MC)</td>
<td>0.1m-0.4m</td>
<td>II</td>
</tr>
<tr>
<td>Cas A</td>
<td>3.4</td>
<td>320</td>
<td>2-10</td>
<td>0.1m-1m</td>
<td>Ib (masive WR star)</td>
</tr>
</tbody>
</table>

(Various references)
More TeV SNRs?

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

- RX J1713.7-3946 (CANGAROO)
- SN1006 (CANGAROO)
- RCW86 (CANGAROO under analysis)
- RX J0852-46 (CANGAROO under analysis)
- Cas A (HEGRA)
- Vela (CANGAROO)
- Crab nebula ("Standard candle")
- ROSAT
- ASCA
- Chandra (optical)

Supernova Remnants (Green 1996)
New entry: TeV J2032+4130

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

Rowell et al., 28th ICRC (2003)
TeV J2032+4130 = Cyg X-3 ???

New entry: SNR RX J0852.0-4622

- CANGAROO 10m result

![Image of Vela SNR with a ~8° area highlighted.]

**Preliminary!**

Number of events per 5°

- 5.3σ excess
  - Gamma-ray signal (ON-OFF)

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

- CANGAROO 10m result

Gammaray signal (ON-OFF)

Tsuchiya et al., 28th ICRC (2003)
Spatial pattern: source population along the Galactic plane?

HEGRA CT system

Galactic plane survey

Puehlhofer et al., 28th ICRC (2003)
活動銀河核 (AGN)

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, ...

銀河系外背景放射 (EBL: Extragalactic Background Radiation) による吸収
- 背景赤外線量の不確定性

銀河の中心
- Accumulation of dark matter ??

銀河系外ガンマ線背景放射
Beaming factor
\[ \delta = \frac{1}{\Gamma (1 - \beta \cos \theta)} > 1 \]

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
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 (1)

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

One-zone SSC model

\[ \square = 14, \quad B = 0.14 \text{G} \]

Synchrotron Self-Compton model (2)

One-zone SSC model

Blazar sequence & SSC model

- \( (v f_v)_{\text{synch}} \sim (v f_v)_{\text{IC}} \)

Ghisellini, astro-ph/0308526
SED of TeV blazars

Costamante and Ghisellini, AA386 (’02) 833
Synchrotron proton blazar model

Target photon

π± cascade

π0 cascade

μ-synch cascade

p-synch cascade

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

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

Mrk 421

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

Correlation is not simple!

"Orphan" X-ray flare

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

Mar 19, 2001

Mar 25, 2001

Harder for stronger $\leftrightarrow$ Constant slope

Why this difference?

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

EBL (Extragalactic Background Light)

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

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.

Kneiske et al., AA 413 (2004) 807

Protheroe & Meyer, PL B493 (2000) 1
TeV gamma-ray absorption on EBL (2)

H1426+428: HEGRA CT system

$z=0.129$

Horns et al., 28th ICRC (2003)

EBL (Extragalactic Background Light)

H1426+428: HEGRA CT system

Intrinsic spectrum

Homs et al., 28th ICRC (2003)
TeV gamma-ray absorption on EBL (3)

T. M. Kneiske et al.: Implications of cosmological gamma-ray absorption. II.

Kneiske et al., AA 413 (2004) 807
Fazio-Stecker relation

Fazio and Stecker, Nature 226 (1970) 135

- Gamma-ray horizon (cutoff) due to the metagalactic radiation field

10 GeV photons can probe the whole Universe!
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 2619]

- **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 $\alpha$-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 $\sigma$</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 $\sigma$</td>
</tr>
</tbody>
</table>

TeV blazar population?

New entry: NGC253 (1)

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

<table>
<thead>
<tr>
<th>SB region</th>
<th>Milky Way</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFR</td>
<td>$10 - 10^2$</td>
</tr>
<tr>
<td>Proton density</td>
<td>$10^2 - 10^5$</td>
</tr>
<tr>
<td>Age of SB region</td>
<td>$10^7 - 10^8$</td>
</tr>
<tr>
<td>Size of SB region</td>
<td>0.1 - 1.0</td>
</tr>
<tr>
<td>B field</td>
<td>$10 - 10^2$</td>
</tr>
</tbody>
</table>

Gamma-ray signal = (ON) – (OFF)

New entry: NGC253 (2)

- Extended halo?

Significance map by CANGAROO

Starburst galaxies observed by Whipple

Table 1. Observed sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>Distance (Mpc)</th>
<th>P density ( (cm^3) )</th>
<th>B field (( \mu G ))</th>
<th>Size of SB (kpc)</th>
<th>Age of SB region ( (10^8 \text{yrs}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M82</td>
<td>(~3.5)</td>
<td>(~10^4)</td>
<td>(~25)</td>
<td>(~0.1)</td>
<td>(~30)</td>
</tr>
<tr>
<td>M81</td>
<td>(~3.5)</td>
<td>(~10^2)</td>
<td>(~37)</td>
<td>(~5)</td>
<td>(~30)</td>
</tr>
<tr>
<td>IC342</td>
<td>(~3.0)</td>
<td>(~10^4)</td>
<td>(~75)</td>
<td>(~1)</td>
<td>(~10)</td>
</tr>
<tr>
<td>NGC3079</td>
<td>(~16)</td>
<td>(~10^3)</td>
<td>(~10^5)</td>
<td>(~1)</td>
<td>(~30)</td>
</tr>
<tr>
<td>MilkyWay</td>
<td>-</td>
<td>(~1)</td>
<td>(~3)</td>
<td>-</td>
<td>(~10^4)</td>
</tr>
</tbody>
</table>

Table 2. A summary of the observations. The flux upper limits are preliminary and correspond to 650 GeV photons, which provide a maximum detection rate of the telescope for observations at 35 degree zenith angle.

<table>
<thead>
<tr>
<th>Source</th>
<th>Exposure (sec)</th>
<th>Typical zenith (degree)</th>
<th>2 ( \sigma ) upper limit (photon ( \text{cm}^{-2} \text{ s}^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>M82</td>
<td>29753</td>
<td>38</td>
<td>8.84 \times 10^{-12}</td>
</tr>
<tr>
<td>M81</td>
<td>36507</td>
<td>38</td>
<td>7.05 \times 10^{-12}</td>
</tr>
<tr>
<td>IC342</td>
<td>22604</td>
<td>37</td>
<td>7.17 \times 10^{-12}</td>
</tr>
<tr>
<td>NGC3079</td>
<td>36468</td>
<td>26</td>
<td>1.58 \times 10^{-11}</td>
</tr>
</tbody>
</table>
**New entry: M87 (1)**

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

![Optical image of M87 with labeled AGN and Jet](image)

AGN $\sim 10^9 M_\odot$ B.H.
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 $2.4\sigma$, 2002-2003 no excess

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**
  - \( L_{\text{synch}} \sim 3 \times 10^{42} \text{ erg/s} \)

- **Misaligned ‘synchrotron proton blazar’ model**
  - \( L_{\text{jet}} \sim 3 \times 10^{43} \text{ erg/s} \)
  - \( B \sim 30 \text{ G} \)
  - Reimer, Donea & Protheroe, APh 19 (03) 559
Galactic diffuse gamma-rays (1)


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

- 60% Excess
- Data $E^{-2.5}$
- Prediction $E^{-2.7}$
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 at the Galactic Center

Signal enhancement due to \textquoteleft cusp\textquoteright structure toward the center?

\[ J(\Psi) = \frac{1}{R\rho_0} \int_{\text{line-of-sight}} \rho^2(\ell) d\ell(\Psi) \]

Bergstroem et al., APh 9 (1998) 137
Explosive dark matter annihilation

Hisano, Matsumoto, Nojiri PRL 92 (2004)

"Explosive annihilation" by non-perturbative effect

Line (Galactic center, J=500)

Continuum (Galactic center, J=500)

Flux (cm$^{-2}$sec$^{-1}$) $\Delta \Omega = 10^{-3}$
“Evolution” of the TeV gamma-ray sky
“Evolution” in number of objects

Log scale

Number of sources vs time

X-rays

γ-rays

EGRET

COS B

SAS-2

VHE γ-rays

ICRC2003

Kifune plot

©Rene Ong 2002
New Cherenkov telescopes

The “Big Four”

MAGIC

VERITAS

HESS

CANGAROO-III
CANGAROO-III: completion in 2004

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
Smithsonian Inst. etc.

Prototype (Aug ’03)

Oct 2005: Completion of Phase I:
4 telescope array

Oct 2007: Completion of Phase II:
7 telescope array
4th generation concepts

ECO-1000 project
MPI Physics etc.

28m telescope at the center of H.E.S.S.
MPI Nuclear Physics etc.

SuperCANGAROO
30m?
Summary

- Very high energy gamma-rays are probing non-thermal, violent Universe.
- TeV gamma-ray astronomy is becoming an indispensable field of astronomy.
- Very high energy sources may contain large varieties, including both galactic and extragalactic objects, which means particle acceleration is a common phenomenon.
- There are some evidences of SNR origin of cosmic rays, but still there is no unambiguous identification of hadrons. More examples and detailed wide-band observations are necessary!
- The “third generation” Cherenkov telescopes are about to increase sensitivity — more fun!