VHE GAMMA RAY ASTRONOMY
PRESENT RESULTS AND FUTURE PROSPECTS

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Max-Planck-Institute for Physics

Masahiro Teshima
Origin of cosmic rays

Cosmic Rays + X → π + X'
π^0 → γγ
π^± → μ + ν
μ → e + νν
Imaging Air Cherenkov Telescope

Typical parameters
- Energy range: 50 GeV ~ 10 TeV
- CR rejection power: >99%
- Angular resolution: ~0.1 degrees
- Energy resolution: ~20%
- Detection area: ~10^5 m^2
- Sensitivity: ~1% Crab Flux (10^{-13} erg/cm^2 s)

Cherenkov Light
50 photons/m^2 (5 pe/m^2) at 1 TeV
⇒ MAGIC 2 x 240 m^2, HESS 4 x 106 m^2
MAGIC Telescopes

Upgrade from MAGIC to MAGIC Stereo
Regular operation since September 2009

Sensitivity 1.6% Crab → ~0.6% Crab (50hrs)
Angular resolution 1.0 deg → 0.06 deg
Energy resolution 25% → 15%

New technologies to lower the threshold energy

- 17m diameter world largest Cherenkov tel.
- 0.1° High resolution camera
- Hemispherical High QE PMT
- Optical fibre analogue signal transmission
- 2GS/sec Ultra Fast FADCs
- Fast rotation for GRB ~20secs/180deg.
- Trigger threshold ~50GeV → ~25GeV
Angular Resolution in MAGIC Stereo

Data and MC agrees very well!!
~ 0.1 degrees at 100GeV
~ 0.5 degrees at 1000GeV
Started regular observations from October 2009

- Better hadron rejection
- Better angular resolution (0.06 degrees)
- Better energy resolution (25%-15%)
- Enhance the sensitivity over the whole energy range

**Stereo event**

**MAGIC I**  **MAGIC II**

**Crab**

**MAGIC mono**

**MAGIC stereo**
Sensitivity of MAGIC Stereo achieved (~0.6% Crab), factor 3 better than mono
Sensitivity of MAGIC Stereo achieved (~0.6% Crab)

Current Simulations

E [GeV]

$E_F(>E)$ [TeV/cm²s]

Background Limited

Signal Limited

Deep TeV Survey ~1 mCrab

Cosmic ray sources Knee in gamma

AGNs, Pulsars GRBs

1% Crab

10% Crab

50hrs

GLAST (1yr)

Cosmic ray sources

Knee in gamma

H.E.S.S.
Crab Nebula 3.5hr observation with MAGIC-Stereo

PRELIMINARY

Smaller error bars in only 3.5 hours
Physics objectives

SNRs
Pulsars and PWNe
Micro quasars X-ray binaries
AGNs
GRBs

Origin of cosmic rays
Dark matter
Space-time & relativity
Cosmology
Gamma-Ray Emission Processes (1) 
Astrophysical process

**Electron acceleration**
- High-energy electron
- Magnetic Field
- 2.7K CMB photon
- \( \propto E^{-2.2} \)
- X-ray (synchrotron)
- Gamma-ray (IC)
- \( \propto E^{-1.6} \)

\[
\left( \frac{dE}{dt} \right)_{\text{I.C.}} = \frac{4}{3} \sigma_T C \gamma_{\text{max}}^2 U_{\text{photon}}
\]

\[
\left( \frac{dE}{dt} \right)_{\text{Sync}} = \frac{4}{3} \sigma_T C \gamma_{\text{max}}^2 \frac{B^2}{2}
\]

**Proton acceleration**
- High-energy proton
- Nucleus
- \( \propto E^{-2.2} \)
- \( \pi^0 \)
- Gamma-ray
- \( \propto E^{-2.2} \)
- \( \pi^+ \)

\[
E^2 \frac{dF}{dE} = \text{Gamma-ray (IC)}
\]

\[
E \frac{dF}{dE} = \text{Gamma-ray (Proton)}
\]

\[
E \frac{dF}{dE} = \text{X-ray}
\]
Gamma ray emission process from DM Annihilation

Dark Matter Annihilations

Bergstrom et al.

New contribution: Internal bremsstrahlung

L.B., P.Ullio & J. Buckley 1998

VHE Skymap

106 sources (45 Extragalactics + 61 Galactics) in Nov 2010
Blazars, FSRQs, FR-I, Starburst galaxies      SNRs, PWNe, Pulsar, Binaries, un-IDs
GALACTIC SOURCES
SNRS, PWNE
Great success!!  HESS galactic plane survey

PWNe, SNRs, Binaries, un-IDs
HESS: Shell type SNRs
RX J1713, RX J0852, RCW86

Index \( \approx 2.0 \)
Break \( \approx 20 \text{TeV} \)

Index \( \approx 2.2 \)
MAGIC: Shell type SNRs IC443(MAGIC J0616)

Composite image with X(Chandra), Radio(VLA), Optical (DSS)

Molecular Cloud
Radio
X-ray
EGRET 3EG J0617+2238
Pulsar CXOU J061705.3+222127

index~3.1

proton spectral break ~ 70 GeV/c
One of the most luminous star forming region (distance ~ 6kpc)
W51C is a medium age (~30kyr) Super Nova Remnant
Shell of the remnant is interacting with surrounding molecular cloud
Discovery by Fermi/LAT (GeV) and HESS (4.4 σ at 1TeV)

Promising candidate SNR to test and study cosmic ray acceleration
MAGIC results for W51C

- Observation: 31.1 h in 2010
- Extended emission: 0.16°
- Maximum of the emission coincides with the shocked cloud regions
- Models based on Fermi / LAT + radio data predict a too softer spectrum than MAGIC sees
- Morphology suggests hadronic or other mechanisms:
  - particle spectrum hardens at high energies
  - High energy particles penetrate more effectively dense regions
  - other sources > 100 GeV
SNRs in different evolutionary stages

We can study SNRs in different evolutionary stages

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<th>Cas A</th>
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<td>50%</td>
<td>25%</td>
<td>5%</td>
<td>10%</td>
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Courtesy of S.Funk
Pulsar Wind Nebulae observation by HESS

- Major galactic TeV source population
  - Associated with relatively young (<10\(^5\) year old) and energetic pulsars

- Generally believed that we see inverse Compton emission of 1-100 TeV electrons

- 1% of Spin-down energy goes to VHE gamma rays
Pulsar Wind Nebula HESS J1825-137 Energy Dependent Morphology

- Major galactic TeV source population
  - Associated with relatively young (<10^5 year old) and energetic pulsars
- Generally believed that we see inverse Compton emission of 1-100 TeV electrons
- 1% of Spin-down energy goes to VHE gamma rays

- Clear evidence for cooling of electrons in the Nebula
Crab Nebula spectrum
Fermi and MAGIC-Stereo

Smaller error bars in only 3.5 hours

PRELIMINARY
MAGIC result: Published in Science in 2008

By measuring the spectrum around cutoff or at high energies is important to distinguish the emission model

Polar cap: double exponent
Outer gap: simple exponent
Crab Pulsar

PhD Thesis of Takayuki Saito 2010
EXTRAGALACTIC SOURCES
Number of extragalactic VHE Sources (45)

- Whipple
- HEGRA
- MAGIC
- VERITAS
- Fermi

Sources:
- Mrk 421
- Mrk 501
- 1ES1959
- PKS2155
- M87
- 1ES2344
- 1H1426
Cosmic Ray accelerator
Active Galactic Nuclei

Gamma factor \( \sim 10 \)

SMBH \( 10^7 - 10^{10} \) M\(_\odot\)

M87 (HST)
Extra-galactic sources

Extragalactic VHE $\gamma$-ray sources

$E_{\gamma}>100$ GeV

45 sources (3 x FR-I, 2 x Starburst galaxies, 4 x FSRQs, 36 BL Lacs)
PKS 2155−304 (HESS Observation)
Spectral Energy Distribution

- Time-averaged SED is well described by a single zone SSC model:

Highest energy electrons ($\gamma_e > 2 \times 10^5$) produce the X-ray emission, but contribute relatively little above 0.2 TeV
Mrk421 MWL SED

Synchrotron

Inverse Compton
FSRQ 3C279 ($z=0.536$) MAGIC
Most distant 100GeV AGN
EBL (Extragalactic Background Light)

Extragalactic Background Light

blazar

γ_{VHE} e^+ e^-

γ_{EBL} IACT

3C279, z = 0.536

3c279, slope -2.5
Primack 05
Kneiske Low
Stecker Base

opacity for gamma-rays

redshift z
EBL upper limit by MAGIC and HESS observations

Probing new range of the EBL

Green line: model of Kneiske et al., tuned to the 3C 279 spectrum using the $\Gamma=1.5$ criterion
Second most distant 100GeV source FSRQ PKS1222 (4C +21.53) (z=0.436)

>10 sigma in 30min

~10mins doubling time maybe inconsistent with EC model
M87 flare in 2008: MAGIC, VERITAS, HESS, VLBA

Model of 43GHz Radio flux using the measured VHE gamma flux
M87 flare in 2008: MAGIC, VERITA, HESS, and VLBA

(A) radio lobe (B), angular resolution of imaging atmospheric Cherenkov telescopes
kilo-parsec plasma jet, 2 kpc (C)
VLBA resolution (43 GHz)
radius of VHE region

(B) 20" (20pc)
30mas (3pc)

(C) 20" (20pc)
X-ray (Chandra)
optical (V band)
radio (6 cm)

(D) 30mas (3pc)
radio (43 GHz, VLBA)
Morphological studies of UHECR potential sources
Cen A (3.4Mpc) & Cen B (56Mpc)
Moskalenko et al. 0805.1260v1
Cen A: HESS detection

Distance: 3.8Mpc
Flux: 0.8% in Crab Unit
Spectral Index: -2.7

Cross: the best location (COG)
Circle: 95% C.L. VHE extension limit

$\mathcal{L}_{\text{VHE}} \sim 2.6 \times 10^{39}$ erg s$^{-1}$
$\mathcal{L}_{\text{UHECR}} \sim 10^{40}$ erg s$^{-1}$
IC310 (FR-I Radio galaxy) is discovered, when observing Perseus cluster / NGC1275

Too bright as an off-axis blazar
Gamma ray bursts

Hypernova!

Binary neutron stars

Afterglow

GRB Blast shock wave

Optical

Radio
10 GRBs observed by Fermi

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<th>GRB</th>
<th>duration</th>
<th># of events &gt; 100 MeV</th>
<th># of events &gt; 1 GeV</th>
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- 71 GeV (16.54s)
- 59 GeV (0.829s)
- 93 GeV (82s)
GRB 080916C
Fermi results
+CTA simulation

- normalize to GBM light curve
- extrapolate GBM+LAT spectra with Y. Inoue EBL
- simulate with D. Mazin’s tool

T. Yamamoto, Y. Inoue & R. Yamazaki

Abdo+ 09

>100 MeV

>1 GeV

>30 GeV
CTA Monte Carlo: Expected Light curve for GRB at z=4.3

CTA performance study by S.Inoue, Y.Inoue, T.Yamamoto, et al

GRB 080916C, z=4.3
\( t_o=35 \) sec (interval d)

array E, exposure 20 sec
EBL: Y. Inoue

By Y. Inoue & S. Inoue using D. Marin's simulation tool for the CTA collaboration

Total excess/bkgd = 4836/5

\( E=30\text{GeV}, 0.5 \text{ sec bin} \)

Time from GRB [sec]

\( E=30\text{GeV}, 0.1 \text{ sec bin} \)

Time from GRB [sec]

from K. Asano
Summary of VHE gamma ray astronomy

- The VHE gamma ray astronomy started with the discovery of VHE emission from Crab by Whipple observatory in 1989

- The third generation telescopes, HESS, MAGIC and VERITAS are increasing the number of VHE sources very rapidly (1-2 sources/months)

- More than 100 of VHE gamma ray sources
  - SNRs, Pulsar, PWNe, Binaries / BL Lacs, FSRQs, FR-I, Starburst Galaxies

- Galactic sources: SNRs
  - We can see several SNRs in different evolutionary stages with the different energy spectra

- Galactic sources: PWNe
  - Most popular galactic sources, asymmetric morphologies, energy dependent morphology

- Nearby bright BL Lacs show the intensity variation of x 50
  - Mkn421, Mkn501, PKS2155
  - Very fast time variations of a few minutes are found in Mkn501 and PKS2155

- Distant sources: 3c279, PKS1222
  - The room for the extra component (Pop-III) in EBL is now very slim
~23m telescopes
4 - 6° FoV
0.08 - 0.12° pixels
Parabolic/Hybrid f/D~1.2

12m telescopes
7 - 8° FoV
0.16 - 0.18° pixels

4-7 m telescopes
8 - 10° FoV
0.2 - 0.3° pixels
DC or SO f/D 0.5-1.7
Possible array configuration

Configuration E:
LST x 4, MST x 23, SST x 32

Acceptance 3km²
Kifune Plot
(expectation from log S - log N)

~3000 sources by GLAST, AGILE
~1000 sources by CTA
One observatory with two sites operated by one consortium

All sky observatory
(2 stations in North and South)

Mainly extragalactic science

Galactic plus extragalactic science

~ 50MEuro
Canaries: La Palma, Tenerife 2400m
Mexico: San Pedro Martir 2800m

~ 100MEuro
Namibia: Kohmas Highland 1800m
Chile: La Silla 2400m
Argentina: El Leoncito 2600m
Argentina: Puna Highland 3700m
Galactic sources

200~400 sources with CTA

Where is PEVATRON???

Simulations: Digel + Funk (Stanford) + Hinton (Leeds)
超新星は銀河宇宙線の源か？
超新星残骸の進化

銀河系外の天体・相対論的ジェットの研究
最高エネルギー宇宙線の起源？

FRI, FRII
Blazars

超巨大BH $10^7$-$10^{10}$ M☉
活動銀河核（赤方偏移 $z<4$）

ガンマ線バースト（$z<6$）
探究的研究 暗黒物質の探索
暗黒物質対消滅からのガンマ線を探すノーベル賞級の大発見なるか？

宇宙はどこまで透明か？ ⇒ 宇宙の星形成史
宇宙論的な距離を飛来する高エネルギーガンマ線

blazar
Extragalactic Background Light
IACT

3C279, z = 0.536
3c279, slope -2.5
Primack 05
Kneiske Low
Stecker Base

Probing new range of the EBL
Green line: model of Kneiske et al., tuned to the 3C 279 spectrum using the Ω=1.5 criterion

APJ 712, 147 (2010)
arXiv: 1001.4531

CTA
Sag. Dwarf
CTA
Gal.Halo
Specification and Physics

- **Sensitivity** x10 \( \left( 10^{-14} \text{erg cm}^{-2}\text{s}^{-1} \right) \)
- **Angular Res.** x3 \((2 \text{ arcmin} @ 1\text{TeV})\)
- **Low Threshold E** x2 \((20-30\text{GeV})\)
- **Energy Res.** x2 \((10\% @ 1\text{TeV})\)
- **Large Accept.** x30 \((3 \times 10^6 \text{m}^2 \text{ >1TeV})\)
- **Fast rotation** 20 sec/180°
- **Better S/N** x3 \(> 99.9\%\)
- **High Time Res.** x10 \(~1\text{sec})\)
- **Flexible modes** Scan / Monitor

**Topics:**
- SNRs
- New sources
- Morphology
- Origin of CR
- Distant AGNs
- GRBs
- Cosmology
- Space and Time
- Galactic diffuse
- TeV - All sky map
- All Sky Observatory
23m Large size telescope and 12m Middle size telescope

23m LST designed by MPI group

12m MST designed by DESY group
4-7m Small Size Telescope

Italian Design 7m

UK Design 4m
Recommendations and supports

ASPERA Roadmap
Magnificent Seven

ASTRONET Roadmap
High Priority project
Ground based projects

8 Infrastructures
from Physics and eng

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Decadal Survey in Astronomy and Astrophysics in US

Ground-based projects ranked in order:

Large-scale

- Large Synoptic Survey Telescope (LSST)
- Innovations Program
- Giant Segmented Mirror Telescope (GSMT)
- Atmospheric Čerenkov Telescope Array (ACTA)
CTA Japan 活動
大口径望遠鏡プロトタイプリング

・CTAは日米欧の国際共同実験
・日本は主にCTA-LST大口径望遠鏡に貢献
・最終的には全体の20%の貢献をめざす
  - 日本グループ70名の研究者
  - ハード: 23m大型望遠鏡8台分のカメラと鏡
  - ソフト: 物理、シミュレーション、データ解析

CTA LST(23m 大口径望遠鏡)

日本グループによる技術開発・技術貢献

高分解能カメラ(MAGIC)

PMT、高圧、アンプ、スイート制御、読み出し回路

7ch 1GHz 超高速波形読み出し回路

1.5m サイズ
高精度分割鏡

大型スパッタリングシェンバー
Cr + Al + SiO2 + HfO2 による
マルチコート（長寿命、増反射）
Summary: CTA

- CTA will provide
  - 10 times better sensitivity
  - wider energy coverage (10GeV-100TeV)
  - All sky observation
  - ~1000 VHE sources

- High quality data will be delivered
  - Better energy resolution (10%)
  - Better angular resolution (2arc min)

- Time schedule
  - Preparatory Phase until 2014
  - Construction phase: 2015-

- Cost ~200MEuro
  - Contribution from CTA-Japan ~20% of total cost

- Expected contribution from CTA Japan
  - LST Camera
  - GHz sampling readout electronics
  - Large size mirrors

よろしくご支援をお願いいたします。