Ground-based gamma-ray astronomy
Ground-based gamma-ray astronomy

German Hermann
MPI-K Heidelberg

- Warm-up
- Detection techniques & experiments
- Selected results from Galactic & extragalactic observations
- The future
The Cosmic Ray Puzzle

- Mostly nuclei $p, \text{He, ... Fe}$
  - also $e^\pm$
  - few $\gamma, \nu$
- Non thermal spectrum
  - $dN/dE \sim E^{-\alpha}$
- Isotropic distribution

Discovery in 1912, but
- Cosmic ray origin?
- Sources?
- Processes?
Potential Sources and Processes

- Super Nova Remnants (SNR)
- Active Galactic Nuclei (AGN)
- Binary Systems
- Pulsar Nebula
- Dark Matter

- SNR as sources of CR
- Acceleration of relativistic particles
- Energy transfer in pulsars
- Environment of neutron stars and Black Holes
- Properties of relativistic jets
- Indirect search for DM
- Cosmology: diffuse EBL GRBs and GRBRs
Tracers to Cosmic Ray Accelerators

Source of Cosmic Rays

$p + p \rightarrow \pi^0 + X + \ldots$

Interstellar magnetic field : $B \sim 3 \mu G$
Curvature radius at 1 TeV : $r \sim 0.3 \times 10^{-3} \text{ pc}$
Tracers to Cosmic Ray Accelerators

Source of Cosmic Rays

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\[ \rightarrow \gamma + \gamma \]

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Tracers to Cosmic Ray Accelerators

Source of Cosmic Rays

\[ p + p \rightarrow \pi^0 + X + \ldots \]

\[ \rightarrow \gamma + \gamma \]

Observables

- Energy Spectra
  - flux, range, shape
- Source Morphology
- Variability/Periodicity
- Multi-Wavelength (radio, IR, optical, X-ray)

Infer properties of primary particle distribution in the sources and their interactions.
Detection rate for (very) high energy gamma-rays

Rate from Crab (E>1 TeV):

\[2.3 \times 10^{-6} / \text{m}^2/\text{sec}\]

(need a pretty large rocket)
The Atmosphere as part of the detector

\[ X_0 = 37.2 \text{ g/cm}^2 \]

\[ \rightarrow \text{Atmosphere} \sim 27 \, X_0 \]

\[ X_{\text{max}} = \frac{\ln E_0/E_c}{\ln 2} \cdot X_0 \]

\[ E_c \sim 80 \text{ MeV} \]
Cherenkov Light
from Air Showers

~ 10 km

Shower Particles

γ-Ray
(100 GeV)

5 nsec

~ 120 m

E_{γ} : 100 GeV

~ 10 Photons/m^2
(300 – 600 nm)
Imaging Atmospheric Cherenkov Telescopes (IACT):

(Whipple, HEGRA, CAT)
CANGAROO, H.E.S.S., MAGIC, VERITAS
Detection of Particles from Air Showers

γ-Ray (e.g. 5 TeV)

Atmosphere as part of the detector

(pretty cost effective ... but: )

Particle Arrays:
Milagro
Tibet Array
others, ...
Background from Charged Cosmic Rays

γ - Ray

Cosmic ray

Cosmic ray

γ - Ray
Detection of VHE γ-rays using Imaging Telescopes

- Image Axis
- Shower Direction
- Intensity
  - Primary Energy
- Image Shape
  - Type of Particle

γ-ray (100 GeV)

10 km

5 nsec

~ 120 m
Detection of TeV $\gamma$-rays using Imaging Telescopes

Stereoscopy:
- Angular resolution
- Energy resolution
- Background rejection
- Sensitivity
How do we get images of the sky?

Sky map of reconstructed shower directions

Angular resolution: 0.05 \( \ldots \) 0.1\(^\circ\)

From T. Weeks (VERITAS)
How do we get images of the sky?

Scans the sky
Generates an image by grazing incidence
Reconstructs shower directions and creates sky map

Radio
X-rays
VHE Gamma
Effective Detection Area

$\gamma$-Ray (100 GeV)

$100000 \, m^2$

H.E.S.S. (Phase I)

Detection area, m$^2$

- KASCADE (1)
- ALTAI (2)
- CORSIKA (3)

Trigger:
2 CT cut of 4, 6 pixels > 4 ph.c.
Major Ground-Based γ-Ray Installations

- MAGIC
- H.E.S.S.
- VERITAS
- Milagro
- Argo/Tibet-III
- CANGAROO 3

4 Telescopes, stereo
2 Telescopes
4 (3) Telescopes, stereo
The MAGIC Telescope(s)

17 meter diameter
236 m² mirror area

Camera:
3.5 deg FoV

Energy threshold:
~50 GeV (<100 GeV analysis)

First telescope operational since 2004
MAGIC: stereo observations since 2009

2 (almost) identical telescopes
→ Stereoscopy
→ better sensitivity
→ lower threshold
VERITAS: since 2007

499 PMT camera

3.5° FOV

Situated at the Whipple Observatory
near Tucson, Arizona
1268m altitude

4 telescopes
100 m2 each
High Energy Stereoscopic System

H.E.S.S. @ Farm Goellschau
Khomass Highlands
1800 m asl
Namibia

© Philippe Plailly

Full Operation since January 2004
The Cameras

Alt-Azm mount
107 m² mirror area
380 mirrors each
15 m focal length
Rigid mount
Optical PSF
~ 0.5 mrad (r80)

5 deg FoV
960 Pixels / PMTs
Fast Trigger [nsec]
GHz sampling, 16 nsec Int.
Field of View on the Sky

Rel. acceptance of the system

- Monte Carlo
- Data
- Background

Field of View of the system for $\gamma$-rays

50% acceptance: 3 deg
20% acceptance: >4 deg

- Sky Surveys
- Extended sources
- Serendipitous discoveries
- High energy performance
Background from Charged Cosmic Rays
Who is who? Gamma-Hadron Separation

Gamma

Proton

Particle tracks in the air

C-photon density on ground

Not to scale
Stereoscopic Hardware Trigger

Telescopes coupled on hardware level ("central trigger")
Who is who? Gamma-Hadron Separation

Particle tracks in the air

Camera plane: angular space

Image Width
Background from Charged Cosmic Rays
Background from Charged Cosmic Rays

\[ \epsilon_\gamma = 0.56 \ldots 0.28 \]

\[ \epsilon_b = 0.03 \ldots 0.004 \] (10 - 20 / h)
State of the Art Performance Parameters

Within a factor 2-3 same for H.E.S.S., MAGIC, VERITAS

Energy range: \( \sim 100 \text{ GeV} \ldots \sim 100 \text{ TeV} \)
Energy resolution: 15 %
Field of view: \( \sim 4 \text{ deg} \)
Angular resolution: \( 0.05^\circ - 0.1^\circ \)
Pointing accuracy: \( \sim 10 \text{ arcsec} \)
Signal Rate: \( \sim 55 \text{ / min (Crab-like)} \)
Sensitivity: 1 Crab in 30 sec
\( 0.01 \text{ Crab in } < 25 \text{ h} \)
Pointed Observations

Survey Instrument

~3-5° FoV

> 90° FoV
Particle Arrays:
Milagro
Tibet Array
Argo-YBJ, …

Detection of Particles from Air Showers

γ-Ray (5 TeV)
Major Ground-Based $\gamma$-Ray Installations
MILAGRO (... - 2007)
MILAGRO: the principle

Water Cherenkov detector

- Use big water pond as particle detector
- Cherenkov light of from air showers particles detected with PMTs
MILAGRO

Near Los Alamos (1999-2007)

2-12 TeV median energy
1700 Hz trigger rate
0.5°-1.4° resolution
1 Crab: $5 \sigma / \sqrt{\text{year}}$
- 6.5 year data set (July 2000-January 2007)
- Crab nebula 15 $\sigma$
- Galactic plane clearly visible
- 8 regions $> 4.5\sigma$ (including Crab)
- Expect 0.04 spots $>4.5\sigma$ in $l\in [30^\circ,216^\circ]$, $b\in [-10^\circ, 10^\circ]$

From S. Casanova
Observational results
The TeV Sky in 2003

4 Galactic
7 Extragal.

from J. Hinton
The TeV Sky in February 2009

58 Galactic
24 Extragal.

from J. Hinton
H.E.S.S. Galactic Plane Survey

Significance of $\gamma$-ray excess

~6°
+65°

Galactic Centre

40++ sources, scale saturated at 20 $\sigma$
Classes of Galactic Sources

- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- Molecular Clouds
- Star cluster
- Pulsar
- Galactic center
- “Dark sources”
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- Supernova remnants
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→ See links to review articles
ASCA SN 1006 data:
“first strong observational evidence that very-high-energy cosmic rays are produced in SNR shocks”

(Koyama, Nature 1995)
TeV Gamma-Rays from SNRs


Largest TeV source: \(~2\) deg diameter

Proof of TeV emission from the shell of SNRs
Proof of TeV emission from the shell of SNRs

Particle acceleration to beyond 100 TeV

Index ~ 2.0
Cutoff or break at ~20 TeV
Index constant across SNR


2004-2006 Data
What particles are accelerated ... ?

Source of Cosmic Rays

Infer properties of primary particle distribution in the sources and their interactions

Observables
- Energy Spectra flux, range, shape
- Source Morphology
- Variability/Periodicity
+ Multi-Wavelength (radio, IR, optical, X-ray)
What particles are accelerated ... ?

$p + p \rightarrow \pi^0 + X + \ldots$

\[\rightarrow \gamma + \gamma\]

Source of Cosmic Rays

... protons?

Infer properties of primary particle distribution in the sources and their interactions

Observables
- Energy Spectra
  flux, range, shape
- Source Morphology
- Variability/Periodicity
+ Multi-Wavelength (radio, IR, optical, X-ray)
What particles are accelerated ... ?

Source of Cosmic Rays

TeV electron

X-ray

synchrotron

Inverse Compton

ext. photon

TeV γ-ray

Observables

• Energy Spectra flux, range, shape
• Source Morphology
• Variability/Periodicity
+ Multi-Wavelength (radio, IR, optical, X-ray)

Infer properties of primary particle distribution in the sources and their interactions

... electrons?
Almost perfect X-ray <-> gamma-ray correlation!

Are the primary particles electrons?

X-ray contours: ASCA
RX J1713: Correlation TeV - CO Data?

Nanten CO – data @ -11 km/sec … -3 km/sec (0.4 …. 1.5 kpc)

Some correlation between gas density and TeV emission
Leptonic emission model for RXJ 1713

Assume Electrons: Synchrotron + Inverse Compton

$P_{\text{Sy}} \propto k\gamma^2 B^2$

$P_{\text{IC}} / P_{\text{Sy}} \propto 1 / B^2$

$P_{\text{IC}} \propto k\gamma^2 U_{\text{rad}}$

Assume Electrons: Synchrotron + Inverse Compton

\[ P_{\text{Sy}} \propto k\gamma^2 B^2 \]

\[ \frac{P_{\text{IC}}}{P_{\text{Sy}}} \propto \frac{1}{B^2} \]

High B-Field

RX J1713: X-rays indicate high B-field

RX J1713.7
Chandra
Uchiyama et al. 2007

Need $B > 1 \text{ mG}$

XMM
Hiraga et al. 2004

Need $B > 65 \mu \text{G}$

Berezkho, Völk 2008
Collision of protons w/ ambient gas: \[ p + p \rightarrow \pi^0 + X \]

Hadronic models describe data reasonably well!

Are SNRs the sources of Galactic cosmic rays??
Unambiguously proof that SNR shock waves are cosmic accelerators up to energies of $O(100 \text{ TeV})$

- **What is the efficiency of energy conversion from SNR explosion into CR**
- **Uncertainty of parameters:**
  - distance $?$, gas density $?$
  - Large lever arm from $O(50 \text{ GeV})$ to $O(100 \text{ TeV})$
  - Further multi-$\lambda$ studies (also GLAST)
  - Better angular resolution (filaments)
  - More sources …
Towards a case by case population study of shell-type TeV SNRs ...

Maps ~ to scale
Classes of Galactic Sources

- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- Molecular Clouds
- Star cluster
- Pulsar
- Galactic center
- "Dark sources"
Discovery Potential: “Dark Sources”

A bias free view on the sky: \(\rightarrow\) new class of TeV sources
No counterparts in other energy bands seen (radio, IR, optical, X-ray, …)

Aligned with Galactic plane
All are extended: ∅ (10 arcmin)
Hard spectrum: \( \Gamma \sim 2.1 \ldots 2.5 \)

→ Maximum energy output of these sources in TeV γ-rays
→ Hadron accelerator ?
→ Old PWN ?
→ GRB remnant ?
→ Dark Matter ?
Discovery Potential: “Dark Sources”

A bias free view on the sky: \(\rightarrow\) new class of TeV sources

No counterparts in other energy bands seen (radio, IR, optical, X-ray, …)

\(\rightarrow\) More sensitive X-ray and radio observations following the TeV detection

Enlightening “Dark Sources”

→ More sensitive X-ray and radio observations following the TeV detection
→ Association / identification as composite SNR (1813) and PWN (1640)

 Hess J1640-465

Color: XMM X-rays

radio contours

Hess J1813-178

Radio shell: Helfand et al., 2005, Brogan et al., 2005

TeV source

Color: XMM X-rays

Funk et al. 2007

Funk et al. 2007

Association / identification as composite SNR (1813) and PWN (1640)
Pulsar discovery triggered by H.E.S.S.

**HESS J1837-069:**
- 7 ' x 3 ' extension
- Flux ~ 0.13 Crab

2 % of dE/dt of Pulsar needed to power TeV flux!

**Discovery of PSR J1838–0655**
- Gotthelf & Halpern (2008)
- period 70.5 ms,
- spin-down energy loss ~$5.5 \times 10^{36}$ ergs/s
The TeV Sky in February 2009

58 Galactic
24 Extragal.
Active Galactic Nuclei (AGN)

Blazars:
• Compact core, high luminosity
• Non-thermal spectrum
• Radioloud
• Polarized -> synchrotron
• Highly variable ( ~ h…y)

26 extragalactic objects detected
- z = 0.002 …. 0.56 (or higher ?)
- almost all are Blazars
- 2 radio galaxies

Black hole of $10^8$-$10^9$ solar masses

Beamed Radiation
„amplified“ intensity shorter timescales
Black hole of $10^8 - 10^9$ solar masses

Synchrotron Self Compton (SSC) Model

Electrons emit **Synchrotron** Radiation in radio - X-Ray

Same Population of Electrons upscatter Synchrotron Photons to GeV-TeV Energies via Inverse Compton
Synchrotron Self Compton (SSC) Model

Electrons emit **Synchrotron** Radiation in radio - X-Ray

Same Population of Electrons upscatter Synchrotron Photons to **GeV-TeV** Energies via Inverse Compton

Main Ingredients:
- Electron Spectrum $K, n_1, E_{\text{break}}, n_2$
- Size of Source
- Magnetic Field $B$
- Doppler factor

Strong X-ray / TeV-correlation expected

Catching the IC-Peak of PKS 2155

Multi wavelength campaign

- Flux close to lowest archival level at X-ray and TeV-energies
- High level of optical flux
- Only little variability (~ 30 %)
- No correlation between X-rays and TeV gamma rays

→ First time, IC peak could be measured for an AGN
→ One zone model fits
→ Highest energetic electrons responsible for hard X-rays, but little impact on TeV gammas
PKS 2155 Monitoring

- Source monitored since 2002 (~240 h)
- Average flux: $3.95 \pm 0.39 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$
- Huge outburst in July 2006 - two main flares of 27 and 29 July

Monthly light curve: 2002 … 2006

![Graph showing the monthly light curve from 2002 to 2006, with a preliminary note.](image)
"Photons from hotter hell" (T. Weekes)

Variability on timescales 2-3 minutes

Characteristic length scale $R_{BH}$

$R_{BH}/c \sim 1...2 \cdot 10^4$ s

Peak flux $\sim 15 \times$ Crab

$\sim 50 \times$ average

Luminosity $\sim 10^{12}$ x Crab

Emission region region Doppler boosted w/ $\Gamma \sim 100$
PKS2155: the Chandra campaign

Multi wavelength campaign : Chandra, RXTE, Swift, Fermi, H.E.S.S. (July 29, 2006)

- Larger flux variations in VHE compared to X-rays and optical
  (1 order of magnitude vs factor ~2 vs <15%)
- VHE / X-ray correlation
- Max luminosity » $10^{47}$ erg/s & $L_{IC}/L_{S}$ from 10 to <1 during the night

PKS2155: spectral variability

H.E.S.S. CHANDRA

Spectral index:
VHE / X-ray correlation
$\Delta \Gamma \sim 0.2$ in X-rays and $\sim 0.6$ in VHE

Flux:
Cubic VHE / X-ray flux correlation
→ a real challenge for SSC models
The future
Near Future: H.E.S.S. Phase II

Improved sensitivity (x1.5 - 2) in current regime up to ~1 TeV

Energy range down to ~50 GeV will finally become accessible
Near Future: H.E.S.S. Phase II
H.E.S.S. Phase II Camera

Same principle as in Phase I:
- Analog pipeline for signal buffering
- On board signal integration

2048 Pixels
Pixel size: 0.07°
FoV: ~ 3.6°

SAM
- Sampling: 1 GS/sec
- Depth: 256 cells
- Bandwidth: > 300 MHz
- Dyn. Range: > 11 bit
Last fall in Annecy ...

H.E.S.S. collaboration in front of camera mechanics test setup (09/2008)
Cherenkov Telescope Array

The very-high-energy ground-based Gamma-Ray Observatory

Photomontage from ASPERA
Next Generation: Wish list

An advanced Facility for ground-based gamma-ray Astronomy

GLAST

MAGIC

H.E.S.S.

Crab
10% Crab
1% Crab

E x F(>E) [TeV/cm²s]

E [GeV]
Next Generation: Wish list
An advanced Facility for ground-based gamma-ray Astronomy

![Graph showing gamma-ray flux vs energy for GLAST, MAGIC, H.E.S.S., and Crab sources.]

- GLAST
  - $E \times F(>E)$ [TeV/cm$^2$s]
  - $10^{-11}$ to $10^{-15}$
- MAGIC
  - $10^{-12}$ to $10^{-14}$
- H.E.S.S.
  - $10^{-13}$ to $10^{-11}$
  - $x 10$
- Crab
  - $10^{-11}$ to $10^{-13}$
  - $10\%$ Crab
  - $1\%$ Crab

German Hermann, MPI für Kernphysik
www.cta-observatory.org
Next Generation: Wish list

An advanced Facility for ground-based gamma-ray Astronomy

- Improved angular resolution
- Source morphology
- Large FoV (6-8 deg)
- Extended sources, surveys
- High detection rate (large area)
- Transient sources

Exploring the cutoff regime of cosmic accelerators

Population studies extended sources
Precision measurements

GLAST

MAGIC

H.E.S.S.

Hi-z AGN and pulsars

1% Crab

x 10

10^{-14}

10^{-13}

10

10^{4}

10^{5}

E [GeV]

E x F(>E) [TeV/cm^2 s]
Low-energy section
a few 24 m telescopes
~ 4-5 deg FoV

Core array:
many ~12 m telescopes
medium FoV (6-8 deg)

Possible Implementation
50-100 telescopes

High-energy section
~ 6 m diameter
large FoV (8-10 deg)
## Tentative Timeline

### An advanced Facility for ground-based gamma-ray Astronomy

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- **Design**
- **Prototype**
- **Array**
The ‘Galactic Plane’ with CTA

Toy Simulation:
- $b$, $l$ object distribution from Parkes, Green & H.E.S.S. catalogues
- $\log(N) = -\log(S)$
- Angular size distribution of objects from H.E.S.S.
- Detector properties (ang. res, S/BG rates) from simulation & data
- Normalized to HESS measurements

‘HESS’ : ~500 hours
The ‘Galactic Plane’ with CTA

Toy Simulation:
- b, l object distribution from Parkes, Green & H.E.S.S. catalogues
- \[ \text{Log (N)} = -\text{log (S)} \]
- Angular size distribution of objects from H.E.S.S.
- Detector properties (ang. res, S/BG rates) from simulation & data
- Normalized to HESS measurements

Expecting / hoping for: \( \mathcal{O}(1000) \) sources (galactic + extragalactic)
The ‘Galactic Plane’ with CTA

6 deg FoV

angular resolution: 0.2 deg (~ 50 GeV)
The ‘Galactic Plane’ with CTA

CTA: a “microscope” for Galactic Accelerators

6 deg FoV

angular resolution: 0.05 deg (> 1TeV)