Short Course on High Energy Astrophysics

Exploring the Nonthermal Universe with High Energy Gamma Rays

Lecture 4: Ground-based gamma-ray detectors: status and future

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Transparency of the Earth’s atmosphere for cosmic E-M radiation

- Radio
- mm
- IR
- O
- UV
- X-rays
- $\gamma$-rays
- HE
- $\gamma$-rays
- VHE

500 km
100 km
10 km
0 km
detection of γ-rays from ground and from space

“direct” detection of LE/HE gamma-rays - possible from space, but is effective only at energies below 100 (10?) GeV

“indirect” detection of VHE gamma-rays - possible from ground, but is effective only at energies above 100 (10?) GeV

recently: detection of gamma-rays from Crab Nebula:
up to 100 GeV by Fermi LAT and down to <50 GeV by MAGIC and HESS

very good agreement of measured fluxes around 100 GeV!
HE, VHE, and UHE Gamma-Ray Detectors

HE
VHE
UHE

direct
Cherenkov light
EAS particles
Ground Based Gamma-Ray Astronomy

presently provides the VHE window in the spectrum of cosmic E-M radiation

0.1 TeV and 100 TeV $\Rightarrow$ TeV (VHE) $\gamma$-ray Astronomy

with a potential for extension of the energy domain

- below 100 GeV down to 10 GeV: multi-GeV (HE) Astronomy
- above 0.1 PeV up to 1 PeV: PeV (UHE) Astronomy

in foreseeable future (hopefully) $\Rightarrow$ GeV-TeV-PeV astronomy
Status of ground-based gamma-ray astronomy

after several decades of struggles and controversial reports/claims ground-based gamma-ray astronomy became an observational discipline - part of modern astronomy/astrophysics with:

- two viable detection techniques:
  (i) Imaging Atmospheric Cherenkov Telescope Arrays
  (ii) Low-threshold EAS arrays/Water Cherenkov Detectors
1950-1970s: first ideas about detection of gamma-rays using ground based detectors - Cherenkov-light telescopes and EAS arrays; first theoretical estimates, first meaningful upper limits; first claims of possible/marginal detections of TeV gamma-ray sources, including Crab (Fazio et al. 1969), and radiogalaxy Centaurus A (Grindlay et al. 1972)

mid 1980s: interesting times with X-ray binaries - exciting reports about detections of TeV/PeV signals (of non-photonic origin?!) from Cyg X-3, Her X-1, …but… unfortunately…

1989: first reliable detection of a TeV gamma-ray signal from the Crab Nebula by the Whipple collaboration (Weekes et al. 1989)

=> finally! ASTRONOMY!

although “a single-source gamma-ray astronomy”
Exciting discoveries by CANGAROO, CAT, HEGRA and Whipple groups (in particular exceptional flares of Mkn 501 in 1997!), but not yet a breakthrough; gamma-ray astronomy recognized as the most advanced area of Astroparticle Physics, but not yet a nominal astronomical discipline; a standard question of opponents: “how many sources do you have?”.

very important - HEGRA group demonstrated the power of the stereoscopic IACT technique with detection of sources at the level of “a few % of Crab”, including two “superstars” on the sky Cas A and M87, as well as the first unidentified (slightly extended!) TeV source => an (obvious?) path towards HESS:

(i) HEGRA concept (stereoscopy and large FoV)
(ii) Whipple type (10m-diameter class) reflectors
(iii) CAT type imagers (multi-hundred channel, fine pixels)

CASA-MIA - giant EAS array: no >100 TeV gamma-ray sources at the level of energy flux 1eV/cm$^2$s
2000s

TeV gamma-ray astronomy - a success story

over last several years the field has been revolutionized

before – “astronomy“ with several sources
(Astroparticle Physics rather than Astronomy)

now – a truly astronomical discipline with characteristic key words:
energy spectra, images, lightcurves, surveys...

with tens (> 150) detected G & EXG sources
and two well established detection techniques
in the energy interval between 0.1 TeV to 100 TeV
the major factors which make possible this success?

several factors… but basically thanks to the lucky combination of two:

✓ great potential of the detection technique

✓ effective acceleration of TeV/PeV particles on all astronomical scales (coupled with favourable conditions for production of gamma-rays)
ground-based technique:

“indirect” - based on the detection of secondary products of air showers or their Cherenkov light

Earth’s atmosphere is not a full absorber, but can be used as a part of perfect $\gamma$-ray detector
Why Cherenkov telescopes?

[CT = an optical reflector with a PMT in focus + fast (ns) electronics]

- large detection area – typically 0.1 km$^2$, potentially up to 10km$^2$ or more

- energy threshold – typically 1 TeV, potentially down to a few GeV

but it is a cosmic ray detector rather than a gamma-ray telescope...
Why Imaging?

- it allows reconstruction of shower parameters!
  - certain information about arrival direction
  - capability to separate gamma- and proton induced showers

**first result:** detection of 10 sigma signal from Crab with Whipple 10 m telescope (1989)

a good gamma-ray detector but not yet a perfect telescope ...
Why Stereoscopy?

- Better separation of hadronic and E-M showers → confidence/reliability, sensitivity
- Angular resolution of about 3 arcmin → sensitivity, source localization, morphology
- Energy resolution 10 to 15 per cent → spectrometry
- Rejection of local muons, better rejection of N.S.B. → low energy threshold, systematics under control
- Quite large (up to 5 degree) FoV → extended sources, effective surveys, larger collection areas

IACT arrays are perfect gamma-ray telescopes!
Detecting Very High Energy Gamma-Rays with Cherenkov Light

At 100 GeV, ~10 Photons/m^2 (300 – 600 nm)

Focal Plane

~ 10 km

Particle Shower

~ 10 km

5 nsec

Image Shape

Intensity

Shower Energy

Background rejection

Image Orientation

Shower Direction
Stereoscopic IACT arrays as perfect $\gamma$-ray-telescopes!

Source is located (somewhere) on the image axis ... 

Need several views to get unambiguous shower direction
\( S_{\text{eff}} = 1 \text{m}^2 \) at 1 GeV

- huge (\( > 1 \text{km}^2 \) or larger) detection area
- good (\( => 1 \text{arcmin} \)) angular resolution
- good (10-25%) energy resolution
- flux sensitivity \( \Rightarrow 10^{-14} \text{ erg/cm}^2 \text{ s} \)
- domain: 0.1 - 100 TeV with a potential of extension down to 10 GeV and up to 1 PeV
H.E.S.S. - High Energy Stereoscopic System

the first representative of the new generation of IACT arrays
HESS II- lower threshold

32.6m X 24.3m dish
Camera FOV 3.5 deg

2048 PMTs
VERITAS

South Arizona
good performance => high quality data => solid basis for theoretical studies

RXJ 1713.7-3946

TeV image and energy spectrum of a SNR

Galactic Center

resolving GMCs in the Galactic Center 100pc region

PKS 2155-309

variability of TeV flux of a blazar on minute timescales

multi-functional tools: spectrometry temporal studies morphology

✓ extended sources: from SNRs to Clusters of Galaxies

✓ transient phenomena μQSOs, AGN, GRBs, ...

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology
towards next generation IACT Arrays:
✓ an order of magnitude better sensitivity
✓ broader energy coverage: $10^{10}$ to $10^{15}$ eV

from HESS/MAGIC/VERITAS to CTA…
two possible designs of IACT arrays (Aharonian 1997, LP97, Hamburg 1997)
two possible designs of IACT arrays

the slide shown first time in Padova in 1995 at the 4th “Towards a major ...” workshop published 2 years later, in: FA 1997, LP97 (Hamburg)

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(a) multi-cell arrays of "100 GeV" class IACTs

- $E_{th} \sim 100\text{ GeV}$
- $\sigma_0 \sim 0.1^\circ$
- $A \Rightarrow 1\text{ km}^2$
- $f_E \Rightarrow 10^{-7}\text{ erg/cm}^2\text{s}$

HESS Phase 1

- 1500-2000m asl
- operation mode: self triggered cells of IACTs

(b) systems of cells of "10 GeV" class IACTs

- $E_{th} \sim 10-20\text{ GeV}$
- $\sigma_0 \sim 0.3^\circ @ 10\text{ GeV}$
- $\sim 0.03^\circ @ 100\text{ GeV}$
- $A \geq 10^4\text{ m}^2 @ 10\text{ GeV}$
- $\geq 10^5\text{ m}^2 @ 100\text{ GeV}$
- $f_E \Rightarrow 10^{13}\text{ erg/cm}^2\text{s} @ 10\text{ GeV}$
- $\Rightarrow 10^{12}\text{ erg/cm}^2\text{s} @ 100\text{ GeV}$
- $< 10^{12}\text{ erg/cm}^2\text{s} @ 1\text{ TeV}$

- >3500m asl
- operation modes:

1. at small zenith angles
   - 3 independent stereoscopic systems of IACTs (at $E < 100\text{ GeV}$)
2. at large zenith angles
   - individual IACTs from different cells - in coincidence (at $E > 100\text{ GeV}$)
THE NEXT BIG STEP:
THE CHERENKOV TELESCOPE ARRAY

10 fold improvement in sensitivity
10 fold improvement in usable energy range
much larger field of view
strongly improved angular resolution
CTA – a powerful tool for exploration of the Nonthermal Universe

- detection of `nominal’ (Fermi/AGILE) AGN for just 1min,
- detection of >10,000 gamma-rays from (Fermi LAT) GRBs with >10-GeV tails

but above several tens of GeV, the emission could be suppressed at tens of GeV

=> low threshold is critical (as low as 10 GeV is possible!)
Air shower detectors

Tibet AS-gamma Experiment
Milagro Detector

- Central Water Pond (80x60 meter)
- 450 PMTs under 1.5 m water
- 273 PMTs under 6 m water
- 2640 meters a.s.l. elevation

- 1700 Hz Trigger Rate
- angular resolution $0.35^\circ - 1.0^\circ$
- energy range: 100 GeV – 100 TeV
  median energy 10 – 40 TeV
  (depending on cuts, weights etc)
- Operated from 2000-2008

energy flux sensitivity compared to Fermi and VERITAS but at 100TeV

Milagro is a quite sensitive instrument!
next step: HAWC (High Altitude Water Cherenkov)

300 close packed water tanks (7.3m dia x 4.5 m deep of 200,000 liters) each with 4 upward facing photomultiplier tubes at the bottom.
HAWC performance

Angular Resolution

Hadron Rejection
from Milagro to HAWC - bigger and higher:
to reduce energy threshold and increase sensitivity

HAWC Site Location

HAWC

Large Millimeter Telescope
(50m dia. dish)

Pico de Orizaba
5600 m
(18,500')
beyond HAWK …

objectives?
- more sensitive – larger array
- lower threshold – higher altitude

purpose?
- all sky monitor with flux sensitivity
  $10^{-12}$ erg/cm$^2$ s - similar to *Fermi LAT*
  but in VHE domain
- transient VHE gamma-ray source “hunter”

plans? LATTES… (ALMA site, 5km a.s.l.)
HIGH-ALTITUDE CHERENKOV TELESCOPES

F. Aharonian et al., astro-ph/0006163
4 x 20 m telescopes @ 5000 m asl

$A_{\text{eff}} = \frac{8.5 \cdot E^{5.2}}{[1+(E/5 \text{ GeV})^{4.7}]} \text{ m}^2$

higher light intensity (5000 m: x2)
→ lower threshold
smaller light pool area (5000 m: /2)

Reference height ~2000 m
5@5 - a GeV timing explorer

- **Detector**: several 15 to 25m diameter IACTs to study the sky at energies from several GeV to several 100 GeV with unprecedented photon and source statistics

- **Potential**: can detect EGRET/Fermi sources with spectra extending beyond 5 GeV for exposure time from 1 sec to 10 minutes

- **Targets**: Gamma Ray Timing Explorer for study of nonthermal phenomena: AGN, Microquasars, GRBs, Pulsars...

5@5 is complementary to GLAST in fact due to small FoV needs very much GLAST and ... GLAST certainly needs a 5@5 type instrument

"The rapid development and successful operation of 5@5 during the lifetime of GLAST would represent a major observational coup"

5@5 – a Gamma Ray Timing Explorer
Future of ground-based gamma-ray astronomy

- **aim?** sensitivity: \( F_E \Rightarrow 10^{-14} \text{ erg/cm}^2 \text{ s} \) (0.03-30 TeV)
- **realization** 1 to 10 km\(^2\) scale 10m+ diameter IACT arrays
- **timescales** short (years) - no technological challenges
- **price** no anymore cheap 100+ MEuro
- **expectations** guaranteed success - great results/discoveries
- **first priority:** "classical" 0.1-30 TeV IACT array with possible extension towards 30 GeV and 100 TeV
- **next step:** (<100 GeV threshold all-sky monitor (LATTES?)
  (parallel?) <10 GeV threshold IACT array (5@5?)
Current Status
>150 TeV sources on the *Fermi* LAT map
VHE Gamma Ray Sources:
not many but representing many source populations

Extended Galactic Objects
✓ Shell Type SNRs
✓ Giant Molecular Clouds
✓ Star formation regions
✓ Pulsar Wind Nebulae

Compact Galactic Sources
✓ Binary pulsar PRB 1259-63
✓ LS5039, LSI 61 303 ?
✓ Cyg X-1 (a microquasar)

Galactic Center

Extragalactic objects
✓ M87, Cen A - radiogalaxies
✓ TeV Blazars - with redshift from 0.03 to 1
✓ NGC 253 and M82 - starburst galaxies
✓ GRBs (Fermi LAT; photons of tens of GeVs at \( z > 1 \))

and a large number of yet unidentified TeV sources ...
Potential Gamma Ray Sources

Galactic Sources

- ISM
- SFRs
- SNRs
- Pulsars
- Binaries
- GMCs
- Magnetosphere
- Cold Wind
- Pulsar Nebula
- Microquasars
- Binary Pulsars

G-CRs

Relativistic Outflows

Compact Objects

Extragalactic Sources

- GRBs
- AGN
- GLX
- CLUST
- IGM
- Blazars
- Radiogalaxies
- Normal
- Starburst

EBL

Major Scientific Topics

42