ISAPP 2019 @ the Pierre Auger Observatory
Cosmic ray Vision from the Southern Sky

March 1-9
Malargüe, MZ, Argentina

COVERED TOPICS:
UHE Cosmic rays
Cosmic rays sources and propagation
Multi-messenger astronomy
Gravitational waves
High-energy neutrinos
Gamma Rays

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Gamma Rays

Johannes Knapp, DESY Zeuthen
Part I: Intro & Techniques
energetic (elementary) particles from space (Sun, Milky Way, distant galaxies) bombard Earth continuously.

Energies from MeV .... >10^{20} eV

1 eV = 1.6 \times 10^{-19} J

most relativistic particles in the Universe

Astrophysics with photons and particles.
Particle physics with probes of astrophysical origin.
What are these cosmic particles?

**must be stable** (to survive travel to us)

- can be accelerated in electric fields
- are deflected in magnetic fields

- move in straight lines
- secondary particles

Cosmic Rays:

- electrically charged
- neutral

- photons, light
- neutrinos

Cosmic Rays:

- protons...
- electrons...
- helium...
- iron...

Other astro particles: **dark matter**

... not in this talk.
Energy scale:

- meV ... eV ... keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV
- $10^{-3} \ldots 1 \ldots 10^3 \ldots 10^6 \ldots 10^9 \ldots 10^{12} \ldots 10^{15} \ldots 10^{18} \ldots 10^{21}$ eV

Photons: astronomy

charged: p, He, ..., Fe, ... completely ionised nuclei electrons

Neutrinos:

the range of astroparticle physics

non-thermal processes
Cosmic rays, gamma rays and neutrinos come likely from the same sources.

- Only charged particles can be accelerated in electromagnetic fields.
- Reactions with fields, gas, dust.

```
p, He, ... Fe
   e
   \pi^+ \rightarrow \pi^0
   \pi^- \rightarrow \pi^0
```

- Difficult to detect.
- Easy to detect: gamma rays, neutrinos.
- Point back to sources (good for astronomy).
- "Multi-messenger astrophysics."

- "but gamma rays are currently the most "productive" messengers."
Cosmic accelerators

The highest-energy particles come from the most violent environments (physics in extreme conditions)

The highest-energy CRs, $\gamma$ and $\nu$, come likely from the same sources.
The Universe is opaque to photons for $\frac{1}{4}$ of the spectrum.
Cosmic particle spectra

steeply falling spectra, low fluxes at high energies require huge detectors
in general: for all particle types

the higher the energy, the lower the flux

the lower the flux, the larger the required detectors

\[ N_{\text{evts}} = \text{flux} \times \text{area} \times \text{time} \]

> 100 small, given by nature

\( \approx 1 \, \text{m}^2 \) for satellite expts.

\( \approx 3 \, \text{yrs} \)

Detector size limits the smallest measurable fluxes.
Large, natural volumes become part of our detectors:

atmosphere, ice shields, oceans, ...

instrument (sparsely) to record secondaries produced by particle interactions

understand / monitor the “target”
primary particle: $E$, $\text{type}$, $\theta$, $\varphi$

indirect measurement: extensive showers (in air, ice, water, …)

measure the shower to identify the primary

<table>
<thead>
<tr>
<th>Energy</th>
<th>shower size</th>
</tr>
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<tbody>
<tr>
<td>Direction</td>
<td>timing</td>
</tr>
<tr>
<td>Type</td>
<td>shower shape &amp; particle contents</td>
</tr>
</tbody>
</table>
CRs: each CR makes an air shower, easy to detect
(difficult to identify the primary)

\( \gamma \): each \( \gamma \) makes an air shower, easy to detect
(but 100 - 10000 x more CRs, separate them from \( \gamma \))

\( \nu \): only very few \( \nu \) interact in/near detector,
high-energy e, \( \mu \), \( \tau \) make showers in ice
(but many atmospheric neutrinos from CR interactions)

serious backgrounds
Backgrounds

Cosmic gamma rays (pointing back at source)
Cosmic nuclei (diffuse)

10000x more abundant

Atmospheric ν
(astrophysical ν (dominant at high energies))
Interactions of radiation with matter

Charged and neutral particles: How to detect them?
Detection of an object relies always on its "interaction" with a detector!

- **vision**: photon absorbed in the eye
- **hearing**: sound wave absorbed in ear
- **liquid level**: liquid changes capacitance

**Particles**: let them ionise atoms & record ionisation charge

- (mostly electromagnetic interaction, atomic physics)

- **charged particles** ($e^\pm$, $\mu^\pm$, $p$, $\pi^\pm$, $\text{He}^{++}$, ...):
  - ionisation, bremsstrahlung, multiple scattering
  - Cherenkov & transition radiation

- **photons**:
  - photo effect, Compton effect, pair production

- **neutrons**:
  - collision and recoil, n-capture

This is the basis of all particle detection.
Ionisation

charged particle \((m, Z\cdot e, v)\) "hits" electron in an atomic shell with its electrical field

Electron feels kick and gains energy, which comes from the passing particle.
maximum velocity: \(v_e \ll v\) for \(M \gg m_e\)

transfer of \(E_{\text{kin}}\) to one electron
\[
\frac{z^2 e^4}{8 m_e \pi^2 \varepsilon_0^2 b^2 v^2}
\]

If energy transfer \(>\) binding energy, then the electron is released from the atom and a free electron-ion pair is produced.
Ionisation processes happen very often and the average over many gives the total energy loss of the projectile.
Ionisation (cont'd)

Bethe-Bloch formula:

\[-\frac{dE}{dx} = K \frac{Z^2}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right] \]

average energy loss (in units of MeV/(g cm\(^{-2}\))) of a charged particle (z, β, γ)
in a medium (Z, A, I, δ)

- x is pathlength in g/cm\(^2\), i.e. independent of density
- small dependence on projectile mass M through \(T_{\text{max}}\)
  \[
  (T_{\text{max}} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2 \gamma m_e/M + (m_e/M)^2} = \text{max. kin. energy transfer})
  \]
- in most materials (except H) particles have very similar energy losses
  (due to \(Z/A \approx 0.5\), for H: \(Z/A \approx 1\))
- dependence on density (via density correction \(\delta\))
- dependent on \(z^2\) and \(\beta^{-2}\) only
- broad minimum at \(p/M = \beta \gamma = 3 \ldots 3.5\) for \(z = 7 \ldots 100\)
  (particles close to minimum: minimum ionising particles, MIPs)
- below minimum: \(-dE/dx \sim \beta^{-2}\) (\(\sim 1/E_{\text{kin}}\))
- above minimum: \(-dE/dx \sim \ln \gamma^2\) slow, logarithmic rise
The Bethe - Bloch Formula

for energy loss of charged particles in matter
logarithmic rise: electric field relativistically compressed, reaches further out to ionise more atoms

\[ v \approx c \]

saturation: atoms shield field in larger distances (density effect)

universal curve: \( \frac{-dE/dx}{z^2} = f(v) \) for (almost) all particles/materials

fluctuations: ionisation is statistical process; \( N_{\text{collisions}} \) and \( dE/dx \) vary

deflection: depends on projectile mass: less for heavy particles (like p) more for light ones (like e)

Applications: if \( E_{\text{kin}} \) known, \( dE/dx \sim z^2 \) is sensible measure for \( z \)

\[ (dE/dx)_{\text{min}} \approx 2 z^2 \text{ MeV}/(\text{gcm}^{-2}) \] also good \( z \) measurement

if particle stopped, energy measurement
Ionisation tracks seen in photographic emulsions as function of $Z$ of the particle.
\( \frac{dE}{dx} \) for different nuclei

\[ 26^2 = 676 \]
\[ 20^2 = 400 \]
\[ 6^2 = 36 \]
\[ 2^2 = 4 \]

**Figure 5.3** Rates of energy loss shown for several particles with different charge \((Z)\). The curves show the \(Z^2\) dependence in their vertical spacing. From 100 to around 800 MeV/n, the energy loss rate decreases with the square of the particle’s speed; after a broad minimum, the loss rate increases only slowly.
Figure 6.2. (a) Nuclear emulsion photographs of the track of a cosmic ray iron nucleus at various stages in its deceleration from relativistic velocities to rest. The distances are the residual ranges at which the track is observed; these positions are shown schematically in (b). (Photograph from M. M. Shapiro and R. Silberberg (1970). *Ann. Rev. Nucl. Sci.*, 20, 328.)
another energy loss mechanism for charged particles

Radiation is always emitted when charges are accelerated (or decelerated) (imagine as transition between unbound states)

in magnetic fields: synchrotron radiation
in static electrical fields: bremsstrahlung (e.g. field of a nucleus) (= braking radiation)

\[-\frac{dE}{dx} \sim \frac{Z(Z+1.3)}{16 \pi^3 \epsilon_0^3 m^2 c^4 \hbar} \ln \left( \frac{183}{Z^{1/3}} + \frac{1}{8} \right)\]

**Bethe-Heitler**

- \(-\frac{dE}{dx} \sim Z^2 \frac{E}{m^2}\) at energies < 100 GeV only important for electrons
  \(m_e/m_\mu = 1/200\) \((dE/dx)_e / (dE/dx)_\mu = 1/40000\)

- \(-\frac{dE}{dx} \sim E\) i.e. exponential form of energy loss
  \((E = E_0 \exp(-x/X_0)) ; -\frac{dE}{dx} = E_0 / X_0\)

radiation length \(X_0\): path length on which the electron is slowed down to \(1/e\) of its initial energy by bremsstrahlung
$X_0$ is characteristic length for a radiation process

(on 1 $X_0$, typically one bremsstrahlungs photon is emitted)

$$X_0 = \frac{716 \text{ g/cm}^2 \text{ A}}{Z(Z+1.3) (\ln 183/Z^{1/3} + 1/8)}$$

from Bethe-Heitler formula

$$X_0 = \frac{716.4 \text{ g/cm}^2 \text{ A}}{Z(Z+1.0) (\ln 287/Z^{1/2})}$$

from fit to experiment (precise within 5% for H and 2.5% for all other elements)

for small electron energies: loss by ionisation is dominant,
for large energies: loss by bremsstrahlung is dominant

critical energy $E_{\text{crit}}$:

(for electrons)

both loss rates are equal

dividing line between ionisation and radiation regime depends on form of ionisation and radiation loss

$$E_{\text{crit}} \approx \frac{610 \text{ MeV}}{Z+1.24}$$

in solids and liquids ($\pm 2.2\%$)

$$E_{\text{crit}} \approx \frac{710 \text{ MeV}}{Z+0.92}$$

in gases ($\pm 4\%$)

from experiments

$E_{\text{crit}}$ for muons:

analogue definition (but much higher energies)

$$E_{\text{crit}} \approx \frac{6224 \text{ GeV}}{Z+2.05}^{0.876}$$

in solids and liquids ($\pm 4\%$)

$$E_{\text{crit}} \approx \frac{7788 \text{ GeV}}{Z+2.01}^{0.888}$$

in gases ($\pm 1.4\%$)

$10^4\times$ higher than for $e^-$
Critical Energy as Function of Z of the Material

**Figure 23.7:** Electron critical energy for the chemical elements, using Rossi’s definition [1]. The fits shown are for solids and liquids (solid line) and gases (dashed line). The rms deviation is 2.2% for the solids and 4.0% for the gases. (Computed with code supplied by A. Fassó.)

**Figure 23.12:** Muon critical energy for the chemical elements, defined as the energy at which radiative and ionization energy loss rates are equal. The equality comes at a higher energy for gases than for solids or liquids with the same atomic number because of a smaller density effect reduction of the ionization losses. The fits shown in the figure exclude hydrogen. Alkali metals fall 3–4% above the fitted function for alkali metals, while most other solids are within 2% of the function. Among the gases the worst fit is for neon (1.4% high). (Courtesy of N.V. Mokhov and S.I. Striganov.)
Copper
$X_0 = 12.86 \text{ g cm}^{-2}$
$E_c = 19.63 \text{ MeV}$

Rossi:
Ionization per $X_0$
$= \text{electron energy}$

Figure 23.6: Two definitions of the critical energy $E_c$. 
### Some Values:

<table>
<thead>
<tr>
<th>Elem.</th>
<th>Z</th>
<th>$X_0$ (g/cm$^2$)</th>
<th>$X_0$ (cm)</th>
<th>$E_{\text{crit},e}$ (MeV)</th>
<th>$E_{\text{crit},\mu}$ (GeV)</th>
<th>$dE/dx$ (MeV/gcm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
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<td>61.28</td>
<td>865 *</td>
<td>370</td>
<td>2927</td>
<td>4.10</td>
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<tr>
<td>He</td>
<td>2</td>
<td>94.32</td>
<td>755 *</td>
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<td>2269</td>
<td>1.94</td>
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<tr>
<td>C</td>
<td>6</td>
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<td>18.8</td>
<td>84</td>
<td>1001</td>
<td>1.75</td>
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<tr>
<td>N</td>
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<td>37.99</td>
<td>47.0 *</td>
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<tr>
<td>O</td>
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<td>34.24</td>
<td>30.0 *</td>
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<td>335</td>
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<td>0.32</td>
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<td>116</td>
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</tbody>
</table>

* gases: for density at standard conditions
Energy of radiated photons:

\[ \frac{dN}{E_\gamma} \sim \frac{Z^2 a^3 h^2 c^2}{m_e^2 c^4 E_\gamma} \sim \frac{1}{E_\gamma} \]

i.e. \[ \frac{dN}{E_\gamma} \cdot E_\gamma = \text{const.} \]

- Each energy interval receives on average the same amount of energy.
- Radiation of photons with up to full electron energy \( E_e \) possible.

\[ \rightarrow \text{catastrophic process} \]

(for ionisation: many, but always small losses, i.e. continuous process)

**total energy loss:** sum of ionisation and radiation

\[ -\frac{dE}{dx} = a \ln(E) + b E \]
### 6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Table revised June 1994. Gases are evaluated at 20°C, 1 atm. (in parentheses) or at STP [square brackets].

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$</th>
<th>$A$</th>
<th>Nuclear $^a$</th>
<th>Nuclear $^b$</th>
<th>Nuclear $^c$</th>
<th>Nuclear $^d$</th>
<th>$dE/dx$</th>
<th>$\rho$</th>
<th>$X_0$</th>
<th>Refractive index $n_f$</th>
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</thead>
<tbody>
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<td>He</td>
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<td>1.01</td>
<td>0.687</td>
<td>0.033</td>
<td>43.3</td>
<td>50.8</td>
<td>[5.103]</td>
<td>61.28</td>
<td>86.5</td>
<td>(0.0383)[0.090]</td>
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<td>1.01</td>
<td>0.687</td>
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<td>43.3</td>
<td>50.8</td>
<td>[5.045]</td>
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<td>65.1</td>
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<td>90.00</td>
<td>1.845</td>
<td>36.66</td>
<td>[30.420]</td>
<td>[3.305]</td>
<td>6.058</td>
<td>36.6</td>
<td>36.1</td>
<td>1.00</td>
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<tr>
<td>CO$_2$</td>
<td>60</td>
<td>84.99</td>
<td>1.931</td>
<td>36.08</td>
<td>36.1</td>
<td>1.00</td>
<td>3.33</td>
<td>1040</td>
<td>1410</td>
<td>1.077</td>
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<td>Shielding concrete $^b$</td>
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<td>Bunsen glass (Pyrex) $^f$</td>
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<tr>
<td>SiC $^c$</td>
<td>62</td>
<td>99.2</td>
<td>1.067</td>
<td>27.69</td>
<td>11.7</td>
<td>2.32$^m$</td>
<td>1.459</td>
<td>1.49</td>
<td>1.459</td>
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<td>Methane (CH$_4$)</td>
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<tr>
<td>Ethane (C$_2$H$_6$)</td>
<td>55.73</td>
<td>75.71</td>
<td>2.334</td>
<td>45.66</td>
<td>3.035</td>
<td>0.5094[1.356]</td>
<td>1.038$^n$</td>
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<tr>
<td>Propane (C$_3$H$_8$)</td>
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<tr>
<td>Isobutane (C$<em>4$H$</em>{10}$)</td>
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<td>Octane, liquid (C$<em>8$H$</em>{18}$)</td>
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<tr>
<td>Polystyrene, scintillator (monomer C$_6$H$_5$CH=CH$_2$)</td>
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<td>Polystyrenocorophyllon (Teflon) (monomer C$_3$H$_4$CH$_2$)</td>
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<td>Polyvinylidenefluoride (PVDF)</td>
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<tr>
<td>Barium fluoride (BaF$_2$)</td>
<td>92.1</td>
<td>146</td>
<td>1.323</td>
<td>9.91</td>
<td>2.05</td>
<td>4.80</td>
<td>1.56</td>
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<td>Barium strontium fluoride (BSF)</td>
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<td>Cerium oxide (CeO$_2$)</td>
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<td>Lithium fluoride (LiF)</td>
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<td>Sodium fluoride (NaF)</td>
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<td>Sodium iodide (NaI)</td>
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<td>Silica Aerogel $^o$</td>
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<td>NEMA G10 plate $^p$</td>
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</table>

$dE/dx$, $X_0$, and $\rho$ are evaluated at 20°C, 1 atm, (in parentheses) or at STP [square brackets].
**Multiple scattering:**

particles are interacting many times when passing through matter. each interaction is connected with a small deflection (the lighter the particle the larger the scattering; largest effect for electrons)

Result: approx. Gaussian distribution of scattering angles

\[ \frac{dN}{d\theta_{\text{space}}} = \frac{1}{2 \pi \theta_0^2} \exp - \left( \frac{\theta_{\text{space}}^2}{2 \theta_0^2} \right) \]

\[ \frac{dN}{d\theta_{\text{plane}}} = \frac{1}{\sqrt{2 \pi} \theta_0} \exp - \left( \frac{\theta_{\text{plane}}^2}{2 \theta_0^2} \right) \]

\( \theta_0 \): width of distribution

\( \theta_0 = \frac{13.6 \text{ MeV}}{\beta c \rho} \)

\( z \sqrt{\frac{x}{X_0}} \left( 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right) \)

\( x/X_0 \) thickness of scattering material in units of \( X_0 \)

\( \theta_0 \sim 1/p \) small deflections for large momenta

**distinguish space and plane:** \( \theta_{\text{space}}^2 \approx \theta_{\text{plane},y}^2 + \theta_{\text{plane},z}^2 \)
Figure 2.4  (left) Tracks of slow electrons showing the large amounts of multiple scattering that result from the electrons’ small mass. Note also the increase in ionization as the electrons slow down. The tracks shown are about 0.2 mm long. (right) Proton tracks (about 0.2 mm long) generally show a much higher degree of ionization and are much straighter, even to the very end where they stop (at top of photo). (Photograph courtesy of Peter Fowler, University of Bristol.)
Fig. 11.5 Sketches showing typical paths for protons, $\mu$-mesons and electrons coming to rest in an absorber (kinetic energies of a few megaelectronvolts). The electrons are lightest and suffer the greatest multiple scattering. As described in the text, for the same incident velocity the stopping power is initially the same and the most energetic particles, the protons, have the greatest range. For the same incident kinetic energy the stopping power is least for the electrons and therefore their path length is greatest. These remarks apply only at energies low enough that there are no energy-loss mechanisms other than loss by ionization. The length of the last electron path is under-represented.
Cherenkov Radiation:

In medium: refractive index \( n = \frac{c_{\text{vac.}}}{c_{\text{med.}}} \)

If a **charged** particle moves faster than \( c_{\text{med.}} \), then it emits "Cherenkov light".

\[ v > c_{\text{med.}} \quad \text{(or} \quad \beta = \frac{v}{c_{\text{vac.}}} > \frac{c_{\text{med.}}}{c_{\text{vac.}}} = \frac{1}{n} \quad \text{or} \quad n \beta > 1 \) \]

(similar to bang of supersonic airplane)

Emission angle:

\[ \cos \theta_C = \frac{c_{\text{med.}}}{v} = \frac{1}{n \beta} \leq 1 \]

For \( v = c_{\text{med.}} + \varepsilon \):

\[ \theta_C \approx 0 \]

For \( v = c_{\text{vac.}} \):

\[ \theta_C = \cos^{-1} \left( \frac{1}{n} \right) \]

Number of photons:

\[ \frac{d^2N_C}{ds \, d\lambda} = 2 \pi \alpha \sin^2 \theta_C \frac{z^2}{\lambda^2} \]

Energy: blue - ultraviolet, \( \approx 10 \, \text{eV} \), peak at short wavelengths

Energy loss negligible compared to ionisation

Applications:

\( \theta_C \) measures \( \beta \) of particle

\( N_C \) measures \( z^2 \), if \( \theta_C \) and \( \lambda \) are known

Is important for particle identification

[Image of blue glow in a nuclear reactor]
Interactions of Photons ($\gamma$) with Matter I:

Photoelectric effect:

$$E_\gamma = h\nu > E_B$$

photon is absorbed, $e^-$ is set free with kin. energy $h\nu - E_B$

binding energy of electron

for $E_B \ll E_\gamma \ll m_e c^2$ photoeffect from k-shell dominant

$$\sigma_k = \frac{e^{12} m_e^{3/2}}{192\sqrt{2}\pi^5 \varepsilon_0^6 c \hbar^4} \frac{Z^5}{(h\nu)^{7/2}}$$

reaction probability ("cross section")

electrons from many shells available:

shell structure reflected in reaction probability

The higher the reaction probability, the smaller the average path length to the next reaction:

$$\lambda \sim 1/\sigma$$

Nobel Prize A. Einstein 1905:

"particle nature of light"

for waves:

energy of released $e^-$ should grow with intensity since $I \sim E^2$ and $F \sim e E$

observed (big surprise):

electron energy depends only on photon frequency!

This means: light comes in "energy packets" of $E_\gamma = h\nu$

(i.e. like a particle).

"Quanta" give natural explanation of experimental results.
Interactions of Photons with Matter II:

Compton effect:
- photon is scattered at a "quasi free" (i.e. loosely bound) electron
- photon looses, e⁻ gains energy
  energy change depends on γ scattering angle:
  \[ \frac{\Delta \lambda}{\lambda_i} = \frac{\lambda_f - \lambda_i}{\lambda_i} = \frac{h\nu}{m_e c^2} (1 - \cos \theta) \]
- maximum change (i.e. max. electron energy): \( \theta = 180^\circ \)

Electron energy \( E_e \) is what can be measured!

Photo effect: (almost) all energy
Compton effect: only part of energy transferred onto electron

Photons of energy \( E_\gamma \)

\( \sigma_C \sim \ln (E_\gamma) / E_\gamma \) maximal for \( E_\gamma \approx 0.1 - 1 \text{ MeV} \)
Interactions of Photons with Matter III:

$e^+e^-$ pair production:

$\gamma \rightarrow e^+e^-$  
photon is absorbed,  
$e^+e^-$ pair is produced  
(only possible if a nucleus takes some momentum)

$E_\gamma > 2 m_e c^2 = 1.022 \text{ MeV}$

$\sigma_{\text{pair}} \sim \frac{28}{9} \frac{Z^2 \alpha^3 (\hbar c)^2}{(m_e c^2)^2} \left[ \ln \frac{183}{Z^{1/3}} - \frac{2}{7} \right]$  
reaction probability ("cross section")

mean free path $\lambda_{\text{pair}} \approx \frac{9}{7} \lambda_{\text{brems}} \approx \frac{9}{7} X_0$  
same length scale than bremsstrahlung

Limit for large energies, i.e. $E_\gamma \gg m_e c^2$
pair production
\[ \gamma \rightarrow e^+ + e^- \]

Figure 5.8  Electron pairs produced by gamma ray photons. At the point where a gamma ray is converted into an electron-positron pair, the two particles are very close together. Their separate tracks can be seen after a short distance. (Photograph courtesy of Peter Fowler.)
EGRET: a pair-production $\gamma$ ray telescope
electromagnetic showers:

bremsstrahlung: \( e \rightarrow e + \gamma \)

pair production: \( \gamma \rightarrow e^+ + e^- \)

cascade of secondaries

very simple model:
each step doubles particle number until \( E < E_{\text{crit}} \)

then ionisation takes over

\[ N \sim 2^t \quad t = x/X_0 \]

\[ E \sim E_0 / 2^t \]

\[ N_{\text{max}} \sim E_0 / E_{\text{crit}} \]

\[ \frac{dN}{dt} \sim \frac{dE}{dt} = E_0 \ b \ (bt)^{a-1} \frac{e^{-bt}}{\Gamma(a)} \sim t^a \ e^{-bt} \]

typical shower curve \((a, b, E_0\) are parameters\)

width of shower:
cylinder with radius \( R_M = X_0 \ 21 \text{ MeV} / E_{\text{crit}} \)

contains 90% of energy
Energy of the primary particle:
from integral over the measured profile

\[ E_0 = \text{const.} \times \int \frac{dN}{dt} \, dt \]

from calibration in the lab.
Fig. 11.8 Two cloud-chamber photographs of electromagnetic showers developing in lead plates (thicknesses from top down 1.1, 1.1, and 0.13 radiation lengths) placed within the chamber which was exposed to cosmic radiation at sea level. There are two views in each photo, obtained by aiming the camera so that it sees simultaneously directly and via a mirror into the chamber. The lower photograph shows a shower which was either started by a photon or missed the sensitive region above the top plate. In both, the growth and attenuation of the shower is evident. Note that many of the tracks have systematic curvature or distortion, probably due to some difficulty in maintaining stable and uniform temperature conditions in the chamber. These photographs were obtained by L. Fussel and used in a talk by J. C. Street which was published in 1939.
\[ \sigma_{\text{photo}} \sim \frac{1}{E_\gamma} \quad \sigma_{\text{Compton}} \sim \frac{\ln E_\gamma}{E_\gamma} \quad \sigma_{\text{pair}} \approx \frac{Z^2 \alpha^3}{(m_e c^2)^2} \]

- \( E_\gamma \leq 0.1 \text{ MeV} \)
- \( 0.1 \text{ MeV} \leq E_\gamma \leq 10 \text{ MeV} \)
- \( E_\gamma \geq 10 \text{ MeV} \)
Figure 24.3: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes:

- $\sigma_{\text{p.e.}} = \text{Atomic photo-effect (electron ejection, photon absorption)}$
- $\sigma_{\text{coherent}} = \text{Coherent scattering (Rayleigh scattering—atom neither ionized nor excited)}$
- $\sigma_{\text{incoherent}} = \text{Incoherent scattering (Compton scattering off an electron)}$
- $\kappa_n = \text{Pair production, nuclear field}$
- $\kappa_e = \text{Pair production, electron field}$
- $\sigma_{\text{nuc}} = \text{Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)}$

From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data 9, 1023 (80). Data for these and other elements, compounds, and mixtures may be obtained from http://physics.nist.gov/PhysRefData. The photon total cross section is assumed approximately flat for at least two decades beyond the energy range shown. Figures courtesy J.H. Hubbell (NIST).
Interactions of Neutrons with Matter

Neutrons are neutral ....

i.e. they can penetrate a lot of matter easily
they have to interact to be detected

- collision creating a charged recoil particle that ionises
  highest energy transfer, if \( m_{\text{target}} \approx m_{\text{neutron}} \)
  best for H (i.e. protons) as targets
  (or H-rich materials: Methane, Carbo-Hydrates, ...)

- neutron capture: e.g. \( n + ^{10}\text{B} \rightarrow ^{11}\text{B} \rightarrow \alpha + ^{7}\text{Li} + \gamma \)
  with detection of the reaction products.

  high n-capture cross section
  \( t \approx 10^{-12} \text{ sec} \)

  1.47 MeV
  0.84 MeV
  0.48 MeV
Some neutron capture cross sections:

<table>
<thead>
<tr>
<th>Element</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>0.00019 barn</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.0035</td>
</tr>
<tr>
<td>Boron</td>
<td>767</td>
</tr>
<tr>
<td>Cadmium</td>
<td>2450</td>
</tr>
<tr>
<td>Samarium</td>
<td>5922</td>
</tr>
<tr>
<td>Gadolinium</td>
<td>49000</td>
</tr>
</tbody>
</table>
Interactions of Radiation with Matter: Summary

- **charged particles:**
  - all charged particles ionise! (most common/important process)
  - charged particles radiate photons:*
    - bremsstrahlung (high energy photons)
    - Cherenkov effect (low energy photons)

- **photons:** are not directly detectable!
  - always need to produce electrons, which are detectable (see above).
    - photo effect (< 0.1 MeV)
    - Compton effect* (0.1 ... 10 MeV)
    - pair production* (> 10 MeV)

- **electrons + photons:** (at high energy, i.e. E > few MeV)
  - bremsstrahlung + pair production: shower development***

- **neutrons:**
  - collision and recoil, n-capture and decay

Detection of a particle goes ultimately always over electric charge!
Gamma Rays

point back

easy to detect

some absorption

… by far most productive messenger at high energies.
How to detect a $\gamma$ ray source in the sky?

Cosmic rays come diffusely from everywhere. $\gamma$ rays come straight from their sources (i.e. point-like)

Search for an excess from a certain point in the sky above the diffuse background.
**γ Rays:**

pick them out of the CR background
point back at sources

< 100 GeV: direct observations on satellites
  γ via direct identification

> 100 GeV: indirect obs. via air showers
  γ via shower shape, muon content
  or via localised excess of events
  from certain sky positions
Altitude Gamma-Ray Detectors
Historic Development

Many slides and historic information from talks by:

R Mirzoyan (HESS Centenary Meeting, Bad Saarow, 2012)
S Sarkar (School for Cosmic Ray Astrophysics, Erice, 2012)
Historic Timeline – Part 1

1910: E Curie observes bluish light in water with Radium salt
1912: V Hess discovers Cosmic Rays
1912: CTR Wilson invents the cloud chamber
1934: P Cherenkov’s brilliant experimental work to explain the bluish light (Cherenkov effect)
1938: P Auger discovers air showers (CR energies up to $10^{15}$ eV a total mystery at the time)

... ingredients ready for gamma-ray astronomy with Cherenkov telescopes.

many discoveries in particle physics using CRs and cloud chambers; interactions, particle production, ...

1948: E Fermi publishes acceleration theory of cosmic rays (... and if protons are accelerated, then there should also be secondary $\gamma$ rays)
1948: P Blackett recognised that Cherenkov light from relativistic particles in air showers ($e^\pm, \mu^\pm$) should contribute to the light of night sky ($\sim 10^{-4}$ ?).
Air shower arrays were used abundantly for cosmic ray research. Some were used to look also for point sources (i.e. photons) in the sky.

*Initially* unsuccessful: sources claimed, but could not be substantiated too much diffuse cosmic ray showers.
Cherenkov light from showers

Galbraith, Jelley (Harwell, UK) record Cherenkov flashes from air showers

garbage can, 60 cm search light mirror, 1 PMT (fast light flashes)

February 21, 1953  NATURE

Light Pulses from the Night Sky associated with Cosmic Rays

In 1948, Blackett suggested that a contribution approximately $10^{-4}$ of the mean light of the night-sky might be expected from Čerenkov radiation produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the

thank Mr. W. J. Whitehouse and Dr. E. Bretscher for their encouragement, and Dr. T. E. Cranshaw for the use of the extensive shower array.

W. Galbraith  
J. V. Jelley
1958: seminal paper by P Morrison

1959: G Cocconi (CERN) suggests to observe the Crab Nebula (ICRC 1959 Moscow)

Crab Nebula 1 TeV

AN AIR SHOWER TELESCOPE AND THE DETECTION OF $10^{12}$ eV PHOTON SOURCES
Giuseppe Cocconi
CERN - Geneva.

1. This paper discusses the possibility of detecting high energy photons produced by discrete astronomical objects. Sources of charged particles are not considered, as the smearing produced by the magnetized plasmas filling the interstellar spaces probably obliterates the original directions of movement.


Therefore: $V_e = 10^{12}$ eV and $R(10^{12} eV) = 10^{-3.2} m^{-2} s^{-1}$.

The signal is thus about $10^8$ times larger than the background (2). Probably in the Crab Nebula the electrons are not in equilibrium with the trapped cosmic rays, and our estimate is over-optimistic. However, this source can probably be detected even if its efficiency in producing high energy photons is substantially smaller than postulated above.

The Jet Nebula: $m = 13.5$, $H = 10^{-4}$ gauss.

$R(10^{12} eV) = 10^{-5} m^{-2} s^{-1}$, still well above the background (2), for this object our evaluation is probably not fundamentally wrong.
Military surplus of
- parabolic search-light mirrors 1-2 m in diameter
- gun mounts with drive systems

G.T. Zatsepin (from GZK cutoff) asked Chudakov to measure the predicted gamma-ray sources. Crimea: Chudakov got 12 parabolic mirrors of 1.5 m made measurements for almost 4 years.

Crimea Experiment 1959-1965

only upper limits

Cocconi’s estimate far too optimistic
First mention of the potential of the stereo imaging

THE ANGULAR DISTRIBUTION OF INTENSITY OF CHERENKOV RADIATION FROM EXTENSIVE COSMIC-RAY AIR SHOWERS

V. I. ZATSEPIN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 2, 1964


The angular distribution of intensity is calculated for the Cerenkov radiation produced in the terrestrial atmosphere by extensive air showers of cosmic rays. Calculations are made for showers arriving from the zenith and for conditions of observation at sea level and at an altitude of 3800 m above sea level. Photographic observation of the shape of the flash of light against the celestial sphere, as obtained in [3,4], is evidently in satisfactory agreement with the calculations.

1. INTRODUCTION

In the registration of extensive air showers (EAS) by means of Cerenkov counters, 1,2 a knowledge of the angular distribution of the Cerenkov radiation is important primarily from the methodological point of view (choice of the angles subtended by the Cerenkov counters to obtain optimal signal-to-noise ratio, estimates of the accuracy of the angular coordinates of high-energy primary particles, and so on). Besides this, the angular distribution of the light from showers is already itself the object of physical investigation, 3 and therefore it is important to ascertain what kind of information about a shower can be obtained from such data.

The present calculation has been made for this purpose, and is based on the following ideas.

Cerenkov radiation is mainly caused by the electronic component, which makes up the bulk of the charged particles in a shower. Owing to multiple Coulomb scattering by the nuclei of atoms in the air, electrons of energy E at a depth y have a Gaussian distribution of distances r from the axis of the shower, and a Gaussian distribution of angles relative to a mean angle d, which depends on r. The dispersions of the transverse and angular distributions depend on E. The energy spectrum of the electrons is an equilibrium one and does not depend on the degree of development of the shower in depth. For the case of primary photons the variation of the electrons with height is taken to be that given by the electromagnetic cascade theory, 4 and for the case of primary protons, that given by the calculations of Nikol’skii and Fomin 5.6 The light emitted by the electrons is at the angle COB, with the direction of their motion. Neither the scattering of the light by density inhomogeneities in the air nor absorption of the light is taken into account.

2. STATEMENT OF PROBLEM AND METHOD OF CALCULATION

The purpose of the calculation is to determine the number 1 of light quanta in the frequency range from f_1 to f_2 that fall on unit area of the earth’s surface at distance R from the axis of the shower, and in the direction from any given point of the celestial sphere.

Let us turn to Fig. 1. Here O is the trace of the axis of the shower on the earth’s surface, D is the point of observation, and A’ is an arbitrary point which is at height h over the level of observation and is characterized by the angular coordinates $\psi$ (the zenith angle) and $\varphi$ (the azimuthal angle). We agree to measure the azimuthal angle from the direction from the point of observation D to the trace O of the axis of the shower on the earth’s surface. The figure OBDC lies in the plane of the drawing, and OOA’B’ in the perpendicular plane. We shall determine for the neighborhood of

V.I. Zatsepin 1965
Ireland: Porter & Jelley 1962-66
First imaging "stereo" telescopes: GT-48 in Crimea 1985-89

A Stepanian
First gamma-ray experiment at Whipple Observatory, 1967-68

Work on the Mt. Hopkins Observatory proceeds at an astonishing pace. The laser and Baker-Nunn systems are now installed and operating and the large optical reflector is scheduled to arrive by the end of next month. In preparation for the LOR installation, Trevor Weekes (above, left) and George Rieke have conducted seeing tests with two movable searchlight reflectors. Look carefully—some outcroppings at the base of Mt. Hopkins are visible upside-down in the reflector.
A SEARCH FOR DISCRETE SOURCES OF COSMIC GAMMA RAYS OF ENERGIES NEAR $2 \times 10^{12}$ eV

G. G. FAZIO AND H. F. HELMKEN
Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Massachusetts

G. H. RIEKE
Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona, and Harvard University, Cambridge, Massachusetts

AND

T. C. WEEKES*
Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona

Received September 3, 1968

ABSTRACT

By use of the atmospheric Čerenkov nightsky technique, a study has been made of the cosmic-ray air-shower distribution from the direction of thirteen astronomical objects. These include the Crab Nebula, M87, M82, quasi-stellar objects, X-ray sources, and recently exploded supernovae. An anisotropy in the direction of a source would indicate the emission of gamma rays of energy $2 \times 10^{12}$ eV. No statistically significant effects were recorded. Upper limits of $3-30 \times 10^{-11}$ gamma ray cm$^{-2}$ sec$^{-1}$ were deduced for the individual sources.
10 m Whipple Telescope built in 1968
1970-80’s: plenty of “discoveries” on 3-4 $\sigma$ level

A.M. Hillas, University of Leeds:

“A physicist’s apparatus gradually learns what is expected of it. It has a dog-like desire to please."

“Concentration” is a good parameter

($>75\%$ of light is concentrated in 2 pixels)

Plyasheshnikov, Bignami (1985) showed that $\alpha$ is a useful parameter

La Jolla, 1985: Hillas suggests to use the “Hillas image parameters”

Gamma showers are:
- slimmer,
- more concentrated
- oriented towards source
1989:
Detection of the Crab Nebula

5σ signal in 50 h, with 159 pixel camera and Hillas image analysis.

9σ significance
1990’s: sources were seen everywhere, up to $10^{15}$ eV

... which could not be confirmed.

Reliable source detection needs $>5\sigma$ significance and independent confirmation.
Proposal for Imaging Air Cherenkov Telescopes in the HEGRA Particle Array

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Electron Detectors: 1 m² scintillation counters for particle density and fast-timing measurements (2 PM’s each), with 5 mm of lead for photon conversion.

- 37 detectors in operation since July 1988 (University of Kiel)
- 159 additional detectors, 90 of them in operation since July 1989, the rest since December 1990 (MPI Munich together with University of Madrid)
- 49 further detectors to increase the detector density in the centre of the array, planned for 1991 (University of Hamburg)

Muon Detectors: 15 m² each, consisting of sandwiches of Geiger tube and absorber layers, planned for 1991/92 (University of Wuppertal together with University of Kiel)

+ 49 Cherenkov-Light Detectors: each consisting of a 20 cm diameter PM and a light-colllecting cone, planned for 1991 (MPI Munich together with University of Madrid)

+ 5 Cherenkov Telescopes: 3 m in diameter with 19 mirrors and 37 PM’s each, imaging technique, planned for 1991/92 (Yerevan Institute of Physics together with MPI Munich and University of Kiel)

Fig. 1: Status and planned extensions of the HEGRA detector array.
CT1 (3 m diam.)
1992 first signal from Crab Nebula

CT2 – CT6: (4 m diam.)
5 more telescopes until 1997.

first successful stereo detection of γ-ray sources
HEGRA detector, including 6 imaging air Cherenkov telescopes
La Palma 1992 - 2002
HESS: High Energy Stereoscopic System
Namibia: Khomas Highlands

Four 12-m telescopes, 960 pixels / camera,
5° field of view
Data taking since 2004

sees Crab in 30 seconds
1% Crab in 25 h

... a major step forward
## Historic Timeline – Part 2

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Year</th>
<th>Discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingredients ready</td>
<td></td>
<td>1948</td>
<td></td>
</tr>
<tr>
<td>Whipple 10-m telescope</td>
<td></td>
<td>1968</td>
<td></td>
</tr>
<tr>
<td>Crab Nebula</td>
<td>PWN</td>
<td>1989</td>
<td>Whipple</td>
</tr>
<tr>
<td>Markarian 421</td>
<td>HBL</td>
<td>1992</td>
<td>Whipple</td>
</tr>
<tr>
<td>Markarian 501</td>
<td>HBL</td>
<td>1996</td>
<td>Whipple</td>
</tr>
<tr>
<td>3C66A</td>
<td>IBL</td>
<td>1998</td>
<td>Crimea</td>
</tr>
<tr>
<td>IES 2344+514</td>
<td>HBL</td>
<td>1998</td>
<td>Whipple</td>
</tr>
<tr>
<td>PKS 2155-304</td>
<td>HBL</td>
<td>1999</td>
<td>Durham Mark 6</td>
</tr>
<tr>
<td>IES 1959+650</td>
<td>HBL</td>
<td>1999</td>
<td>Telescope Array</td>
</tr>
<tr>
<td>RX J1713.7-3946</td>
<td>Shell</td>
<td>2000</td>
<td>Cangaroo</td>
</tr>
<tr>
<td>Cas A</td>
<td>Shell</td>
<td>2001</td>
<td>HEGRA</td>
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<tr>
<td>Bl Lac</td>
<td>IBL</td>
<td>2001</td>
<td>Crimea</td>
</tr>
<tr>
<td>H 1426+428</td>
<td>HBL</td>
<td>2002</td>
<td>Whipple</td>
</tr>
<tr>
<td>TeV J2032+4130</td>
<td>UNID</td>
<td>2002</td>
<td>HEGRA</td>
</tr>
<tr>
<td>M87</td>
<td>FRI</td>
<td>2003</td>
<td>HEGRA</td>
</tr>
<tr>
<td>Galactic Centre</td>
<td>UNID</td>
<td>2004</td>
<td>Cangaroo</td>
</tr>
</tbody>
</table>

... 16 new sources 2005
... 17 new sources 2006

H E S S started observations ~10 years

first detection ~40 years

~5 years
Cosmic rays, gamma rays and neutrinos come likely from the same sources.

Reactions with fields, gas, dust.

Only charged particles can be accelerated in electromagnetic fields.

Difficult to detect but gamma rays are easy to detect and point back to sources (good for astronomy).

“Multi-messenger astrophysics” but serious backgrounds.

But gamma rays are currently the most “productive” messengers.
Gamma Ray Production

- Synchrotron
- Inverse Compton
- \(\pi^0\) production

Energy flux/Decade: \(E^2 F(E)\)

Cosmic proton accelerators
Cosmic electron accelerators
Synchrotron radiation
Inverse Compton upscattering

Gamma Ray Production:
Radio
Infrared
Visible light
X-rays
VHE gamma rays
Experiment Types

Air shower arrays
Imaging Cherenkov telescopes
Altitude Gamma-Ray Detectors

- HAWC
- Milagro
Argo

gamma sources

RPCs full coverage

4200 m.a.s.l.
Tíbet AS Gamma

4200 m.a.s.l.
Milagro 2650 m.a.s.l.
New Mexico

80 m x 60 m water pond
8 m deep.

Detect shower particles via Cherenkov light in water
PMTs in 2 layers for el.mag. and muons.

look for excess: gamma sources
$2\pi$ sky view
poor $\gamma$-hadron separation via muon content or particle pattern at ground

$\gamma$ sources detected by excess counts from certain directions

sources: Moon, Sun shadow Crab nebula few strong $\gamma$ sources
Moon Shadow ... calibration of direction reconstruction

$E \approx \text{TeV}$

Tibet ASy

Argo

![Diagram showing Moon Shadow and direction calibration]
Heliotail Geminga

Milagro

15.0 $\sigma$ and 12.7 $\sigma$ fractional excess: $\approx 5 \times 10^{-4}$

Tibet

Significance ($\sigma$’s)
MILAGRO
gal. plane

EGRET sources
MILAGRO

(3 \sigma)

strong Fermi sources
... or sample the light pool and measure the lateral distribution.

Good, calorimetric energy measurement.
Hegra, Airobiccc
La Palma

scintillator array
Muon detectors
Cherenkov counter
HAWC: high-altitude water Cherenkov detector
NASA’s Compton Gamma Ray Observatory

1991 - 2000

271 gamma sources (>100 MeV)

$^{26}$Al sky map

2000 GRBs
Fermi Satellite

LAT: 10 MeV - 300 GeV
BGO: ....
GBM: 10 keV-1 MeV

≈ 1 m² 2.5 sr
LAT: 10 MeV - 300 GeV

> 5000 sources
> 50 MeV - 1 TeV
> 5000 GRBs
Fermi - LAT

large angle telescope

pair-conversion telescope with:
precision trackers
  18 layers tungsten converters
  and x, y silicon strip detectors.
calorimeter
  96 CsI(Tl) crystals in an
  8 layer hodoscope (depth: 8.6 X₀)
4x4 modules covered by
anti-coincidence shield

≈ 1 m² 2.5 sr
near-perfect rejection of charged primaries
Fast charged particle in air shower produce Cherenkov light. (forward emission)

“Photograph” shower with an imaging telescope.

Reconstruct identity (\(\gamma, p, \ldots\)) and energy of primary and direction to source.

Cherenkov Telescopes
most sensitive instruments for gamma ray astronomy.

<100 GeV .... >300 TeV

only in dark nights (10% duty cycle)
need good knowledge of atmosphere
Image the shower, distinguish protons and photons from the shape of the images. .... very successful technique

also possible to identify e⁻ and Fe

“shower shape” “excess of events”
~ 10 km

particle shower

~ 120 m

large effective detector area
≈ 10^5 m^2

Detection principle

Photon

1°

Cherenkov light

≈ 1 m^2

~ 10 km

~ 120 m

98
stereo observation: good determination of direction
MAGIC camera

image analysis: form and orientation
e.g. HESS Observatory (28-m Telescope added in 2012)
Namibia: 0.5 km$^2$
5 imaging Cherenkov telescopes

TeV-Gamma rays
($E \approx 10^{11} - 10^{14}$ eV)
Current imaging Cherenkov telescopes