Calorimetry in Particle Physics

Lecture VI Natural Calorimeters

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OUTLINE

I. **Neutrino Telescopes in the Sea**
   1. **Performance characteristics**
   2. **Projects**

II. **Arctic Ice**
   1. **ARMANDA**
   2. **ICECUBE**

III. **Calorimetry in the Earth Atmosphere**
   1. **Telescopes for VHE gamma observations**
   2. **IACTs**
   3. **MAGIC**

Telescopes for VHE gamma observations

- **Cherenkov telescopes**
- **MAGIC: an IACT complex on LaPalma**
- **HESS: a development of the former HEGRA stereo system, now in the southern hemisphere**
- **CANGAROO: the first in the southern hemisphere**
- **VERITAS: Stereo successor to Whipple**
- **The Telescope Array: using Cherenkov and fluorescence detectors**

- **More gamma-ray experiments**
- **STACEE: A solar plant used as Cherenkov detectors**
- **GLAST: the Gamma-ray large area space telescope, a multi-agency mission planned to be launched in 2006**
- **AGILE: an Italian collaboration around a light imaging detector, launch could be in 2005;**
- **SWIFT: a gamma-ray burst mission, launch foreseen in 2004**
- **MEGA: future gamma-ray experiments on board a satellite, i.e. much improved successors to EGRET.**
- **CELESTE: a solar tower (Themis) converted into a Cherenkov experiment**
- **INTEGRAL: European (ESA) astronomical satellite**
- **XMM-NEWTON: an X-ray mission by the European Space Agency**
- **AUGER: a facility for high-energy cosmic rays**

Imaging Air Cherenkov Telescopes (IACTs)

- **IACTs are detectors for high-energy gamma quanta, installed on the surface of the earth.**
  - **The detectors used have a light collection mirror and a camera, so they resemble optical telescopes at least superficially**
  - **These telescopes detect light produced by the Cherenkov effect, a radiation emitted by relativistic particles when being slowed down; the slowing down is in the atmosphere, where the high-energy gamma quanta get absorbed.**
  - **IACT-s record many Cherenkov photons for a single original gamma; they are seen by the camera as an image whose characteristics allow to identify the recorded particle as a gamma, and to specify its direction and energy.**

IACTs

- IACTs target the observation of highly energetic photons from sources within and outside our galaxy, by terrestrial telescopes.
- These photons are not directly observable: because the atmosphere has only narrow windows for wavelengths to pass, and high-energy gamma rays do not reach the earth. They get absorbed in the atmosphere, transparent essentially only for visible and infrared light, and for long radio waves, as shown in the diagram below for the entire electromagnetic spectrum.
- The absorption of the primary gamma leaves behind an avalanche, called an electromagnetic shower. The numerous secondary charged particles in such a shower, for an incident gamma rather exclusively electrons and positrons, all radiate low-energy (visible to ultraviolet) photons, the Cherenkov radiation. The radiation is emitted at a characteristic angle with the radiating particle, an angle which widens as the atmosphere thickens.
- Most of the shower development happens at an altitude above sea level from 20 to below 10 km. The radiated photons have an energy corresponding to a window of penetration, and arrive in large enough numbers on the surface of the earth to become an indirect image of the shower, allowing identification against backgrounds and reconstruction of the original particle's direction and energy.
- Those familiar with high-energy physics instruments can consider the atmosphere as an unbounded and changing total absorption calorimeter, and the Cherenkov radiation observed as part of shower leakage - difficult conditions indeed.

IACTs

- The showering process and the generation of Cherenkov light in a forward cone have two immediate experimental consequences:
  - the light is spread over a large area, typically a circle with a diameter of 250m,
  - and hence the light intensity per unit area on ground is low.
- This allows detection of a gamma impinging anywhere inside this disk, i.e. an effective area of 30 to 100 000 sq.m., as long as the initial energy is high enough to produce enough Cherenkov light.
- Conversely, the signals are weak, marginally detectable; hence, the instrumental sensitivity must be pushed as far as possible:
  - the collection area (mirror surface) must be maximized,
  - the camera elements (photomultipliers) must respond to single photons with high efficiency.
- To further improve sensitivity, experiments are installed on mountain tops far from background light and with as little observation time lost due to clouds as possible.

IACTs

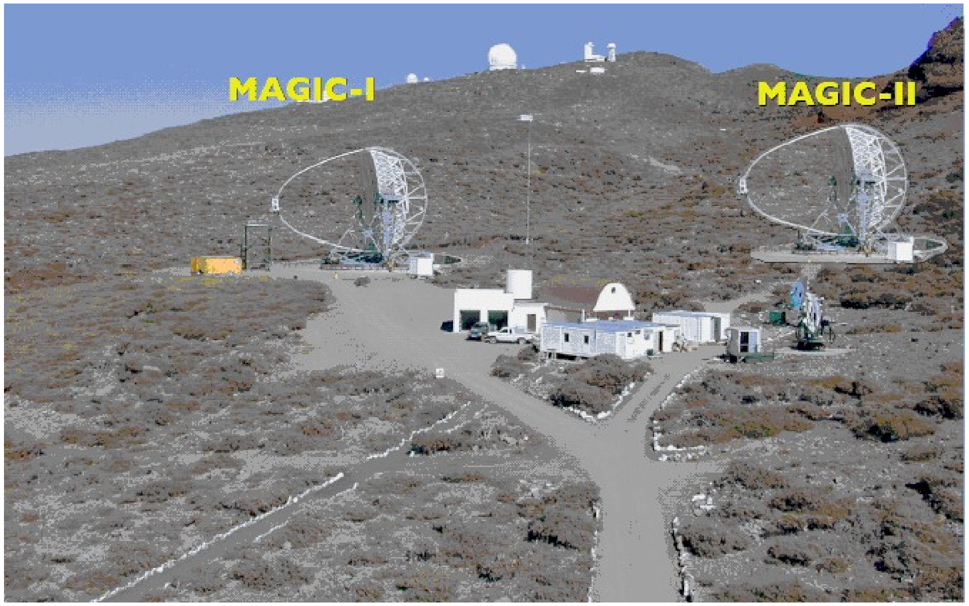
- Electromagnetic showers develop in the atmosphere, and the image it causes in a telescope whose axis is aligned with the shower axis, and which is inside the shower cone (a circle of some 250 m diameter on the surface of the earth).
- Gammas of the high energies that can be recorded by IACTs are relatively rare events. They have to be discriminated against a cosmic ray background several orders of magnitude more abundant.
- These are mostly protons or light ionized atoms, producing (more dissipated) hadronic showers, in which the charged particles also radiate Cherenkov photons.
- However, hadronic showers do not typically come from the direction in which the telescope is trying to observe a gamma source.
- Hadronic showers are much less concentrated; the hadrons interact via the strong interaction, producing hadrons and leptons as secondary particles; multiple electromagnetic and hadronic secondary showers appear, with large fluctuations in relative energy, spread over a volume much larger than for an electromagnetic shower.
- The image hadrons produce in the detector, therefore, has characteristics different from gamma shower images; using suitable discrimination algorithms, fairly clean gamma signals can be obtained

IACTs

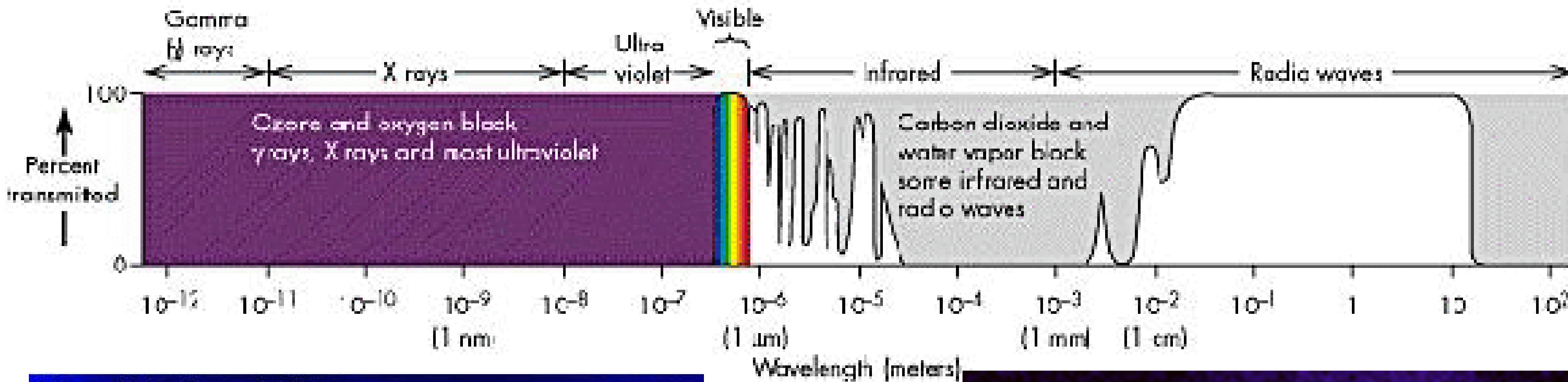
- The recording of images in a Cherenkov telescope has quite different constraints from what optical telescopes require. The phenomenon to be studied, the electromagnetic shower, is comparatively large, and the extraordinary resolution of CCDs (which have replaced photographic file in most optical telescopes) is not required, nor is the ultimate precision in the mirror surface.
- Instead, sensitivity to single photons and the best possible time resolution are important, because the signal is weak, and the discrimination against non-electromagnetic showers is helped by determining precise arrival times.
- Highest-quality photomultipliers are used, therefore, their size matched to the resolution of the shower.

MAGIC

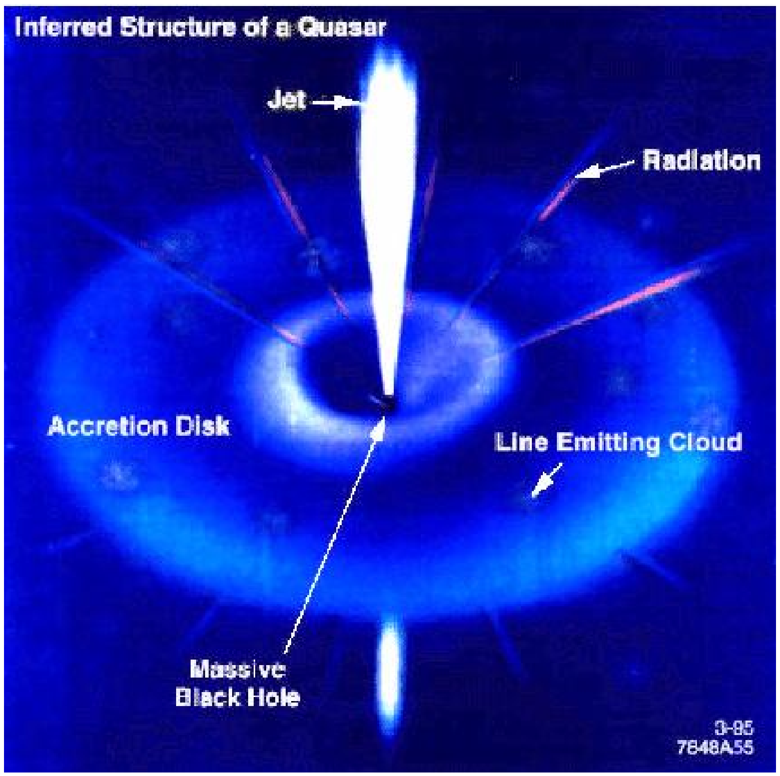
- **The MAGIC Telescope Collaboration has built (2001/2003) a very large atmospheric imaging Cherenkov telescope, with a mirror surface of 236 m2. With this device it will be possible to detect cosmic gamma-rays at an energy threshold lower than any existing or planned terrestrial gamma-ray telescope (the target is < 30 GeV).**
- **Physics:**
  - **Active galactic nuclei**
  - **Supernova remnants**
  - **Sources found at lower energies but not yet identified**
  - **Gamma Ray Bursts**
  - **Other contributions to cosmology and fundamental physics**



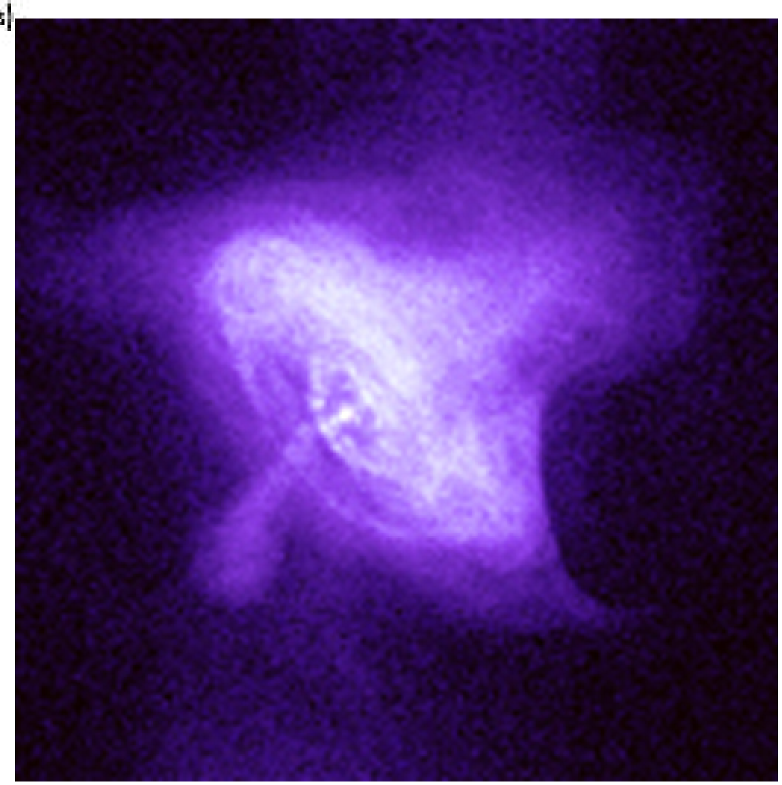
MAGIC



Gamma rays
X rays
Ultra violet
Visible
Infrared
Radio waves
100
0
Percent transmitted
Ozone and oxygen block γ rays, X rays and most ultraviolet
Carbon dioxide and water vapor block some infrared and radio waves
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2}
(1 nm)
(1 μm)
(1 mm)
(1 cm)
Wavelength (meters)



Inferred Structure of a Quasar
Jet
Radiation
Accretion Disk
Line Emitting Cloud
Massive Black Hole
3-85
7848A55



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- MAGIC
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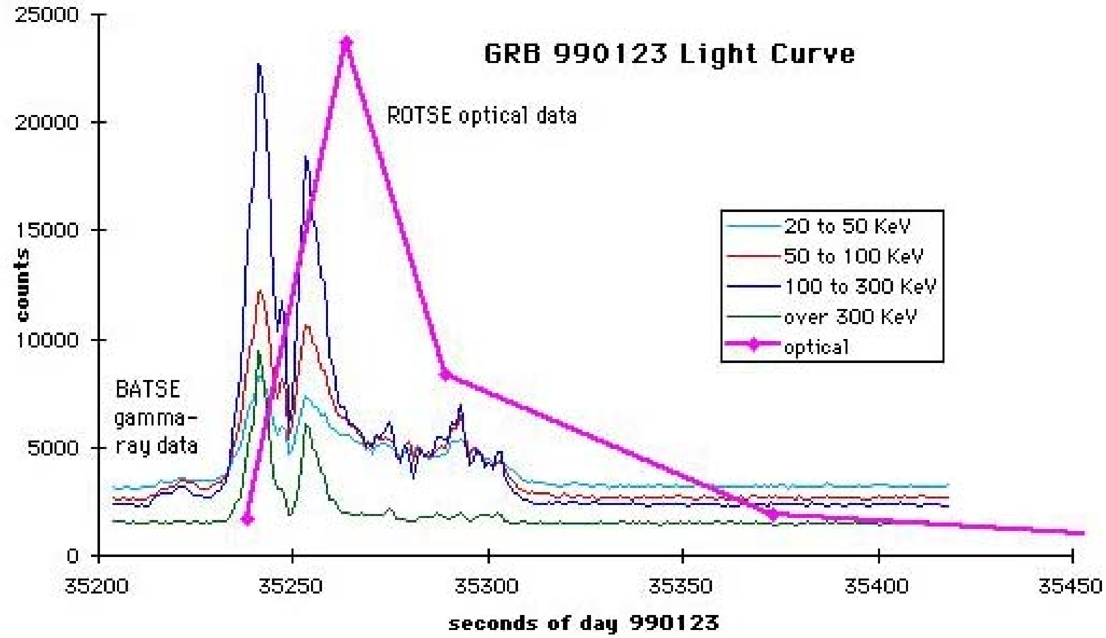
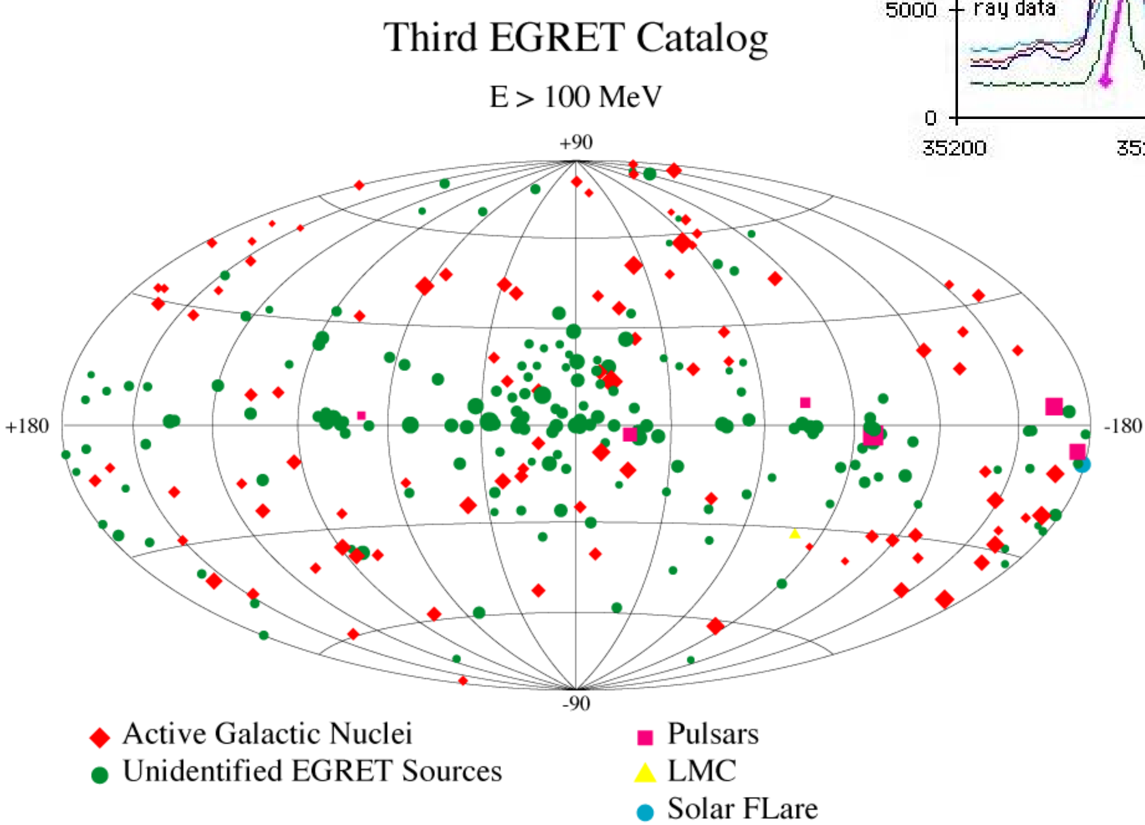

GRB 990123 Light Curve
ROTSE optical data
BATSE gamma-ray data
counts
seconds of day 990123
20 to 50 KeV
50 to 100 KeV
100 to 300 KeV
over 300 KeV
optical
25000
20000
15000
10000
5000
0
35200
35250
35300
35350
35400
35450


Third EGRET Catalog
E > 100 MeV
+90
-90
+180
-180
Active Galactic Nuclei
Unidentified EGRET Sources
Pulsars
LMC
Solar FLare

A second MAGIC - type telescope

- **The MAGIC Collaboration has decided to build (2005 / 2006) a second telescope, on the same site on La Palma, at 85m distance from MAGIC-I.**
- **New technologies and experience with MAGIC-I suggest changes in several areas, all aiming at the best possible performance for low-energy showers with their modest photon yield:**
  - **advanced photosensors with higher sensitivity**
  - **increased camera area instrumented with small-size pixels**
  - **mirror elements with larger surface**
  - **digital signal readout with improved time resolution**
- **For photon sensors, recent industrial developments are under test (hybrid photon detectors with a GaAsP photocathode)**
- **Silicon PMTs (also called Geiger-mode avalanche photodiodes) are in a longer-term development.**
- **Mirrors can now be machined up to one square meter, local assembly of modules.**
- **Higher-frequency digitizing is now offered commercially, permitting better time resolution of signals.**