ULTRA HIGH ENERGY COSMIC RAYS

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Outline

- Introduction
- UHECRs Detection
- Recent Progress
- Propagation
- Acceleration
- Future
Cosmic Ray Spectrum

Indirect measurements

Scaled flux $E^{2.4} \times J(E)$ [km$^{-2}$ yr$^{-1}$ sr$^{-1}$ eV$^{-1}$]

- Tibet&QGSJET
- KASCADE&QGSJET
- AGASA, Ex0.80
- HiRes I/II
- Auger SD&FD, Ex1.15

Energy [eV/particle]

- Knee
- Ankle
- LHC
One century of Cosmic Rays

[Graph showing a line plot with altitude (km) on the y-axis and intensity (ions/cm³) on the x-axis. The plot includes a historical photograph of people on a hot air balloon.]
Cosmic Ray Spectrum

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Energy [eV/particle]

Knee

Ankle

LHC

UHECRs
Extensive Air Showers

Cosmic ray nucleon

Air nucleus

Leading nuclear fragments

Nucleon cascade very close to the core

Pion cascade muons at ground level

Electromagnetic cascade electrons, positrons and photons at ground level
Detection methods

Air shower arrays
• Most frequent technique used
• Scintillators, Water Cherenkov detectors, muon detectors and Cherenkov telescopes
• Particle density gives information on the primary energy
• Time profile from muons and Cherenkov light carries the memory of their production point and can be used for composition

Fluorescence detectors
• Fluorescence light is emitted isotropically
• Proportional to the number of electrons in the EM cascade
• Time profile reflects the evolution of the EM cascade
• Direct measurement of composition ($X_{\text{max}}$)
Air shower arrays

Scintillator detectors

• **Volcano Ranch**
  
  Array of 3 m$^2$ scintillators separated by 900 m in 8 km$^2$
  
  First event with $E \sim 10^{20}$ eV (Linsley et al., Phys. Rev. Lett. 6, 485, 1961)

• **Akeno Giant Air-Shower Array (AGASA)**
  
  Array of 2.2 m$^2$ scintillators covering 100 km$^2$
  
  Ran from 1990 to 2004

• **Telescope Array (TA)** – Surface detector
  
  Array with 507 scintillators covering $\sim$760 km$^2$, separated by 1200 m
  
  In operation since March 2008

• Aperture with scintillators is restricted to 45°

• Energy calibration based on simulations: major problem of the technique
Air shower arrays

Water Cherenkov detectors
- Haverah Park
  Water Cherenkov array with 12 km²
  Worked for 20 years

- Pierre Auger Observatory – Surface detector
  10 m² water Cherenkov detectors, separated by 1500 m covering 3000 km²
  In operation since 2004

  • Sensitive to EM component as well to muon particles (which deposit 10 times more light than a single 20 MeV electron)
  • Very large aperture (up to nearly horizontal showers)

Cherenkov light
- Cherenkov intensity is proportional to the primary energy
- Slope of the lateral distribution is related to the depth of the maximum shower development (composition)
- Main disadvantage: very dense arrays (impossible for E > 10^{17} eV)
Fluorescence detectors

Fluorescence telescopes

• Fly’s Eye
  First fluorescence detector installed at Utah
  Showed the potential of the technique and took data from 1981 to 1993
  Registered the highest energy shower ever detected $3.2 \times 10^{20}$ eV

• HiRes
  Update version of Fly’s Eye designed to measure the fluorescence light stereoscopically
  Ran from 1997 to 2006

• Pierre Auger Observatory – Hybrid detection with WCD
  Same principle that HiRes but integrated to the surface detector
  24 telescopes distributed in 6 buildings

• Telescope Array (TA) – Hybrid detection with a scintillator array
  12 new telescopes distributed in two buildings and 14 telescopes from HiRes placed in a third station
Open questions

- Where do they come from?
- How can they be accelerated to such high energies?
- What kind of particles are they?
- What is the spatial distribution of their sources?
- What do they tell us about these extreme cosmic accelerators?
- How strong are the magnetic fields that they traverse on their way to Earth?
- How do they interact with the cosmic background radiation?
- What can we learn about particle interactions at these inaccessible energies?

Recent Progress

- Spectrum
- Anisotropy
- Composition
Spectrum

Ankle

- Galactic mix & Pure iron: Transition from Galactic to Extragalactic component
- Proton dominate models: Pair production propagation losses (dip models)

Ankle

\[ \log_{10} (E_{\text{ankle}}/\text{eV}) \]
TA: \( 18.69 \pm 0.02 \)
Auger: \( 18.61 \pm 0.01 \)

Cut-Off

\[ \log_{10} (E_{\text{cut-off}}/\text{eV}) \]
TA: \( 19.68 \pm 0.04 \)
Auger: \( 19.63 \pm 0.02 \)
Ankle

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Cut-Off

\[ \log_{10}(E_{\text{cut-off}}/\text{eV}) \]

TA: \( 19.68 \pm 0.04 \)
Auger: \( 19.63 \pm 0.02 \)

Compatible with the GZK cut-off prediction (no need of exotic models)
Maximum energy of acceleration at the source not discarded
Spectrum

Ankle

• Composition studies
• Large scale Anisotropy studies

See Lyberis’s Talk

Flux suppression

• GZK feature: supporting evidence from the spectral shape, anisotropies and composition at trans-GZK energies
• Observation of secondaries such as neutrinos and photons

See Lyberis’s Talk

Also: Go to low energy (~ 10^{17} eV)
Anisotropy at trans-GZK

Anisotropy studies for UHECR

**Auger:** correlation of the UHECR with the nearby AGNs

Best correlation for:
- angular window $\sim 3^\circ$
- $E > 5.7 \times 10^{19}$ eV
- Maximum distance: 75 Mpc

Initially 69% of correlation

Update: 38% of correlation

**HiRes:** repeated the analysis (as close to the Auger one) and did not find any excess (15% of correlation)

Field of view (FOV) is not the same that Auger and the AGNs catalogue has different coverage for different FOV
Anisotropy at trans-GZK

Search for sources in the nearby extragalactic Universe
Sources must lie within ~ 100 Mpc (GKZ-horizon)

- Light composite nuclei are promptly dissociated by cosmic background photons
- Protons and iron nuclei may rich the Earth

- Arrival direction distribution anisotropic:
  - Local matter is inhomogeneously distributed
  - Magnetic field not too strong
Anisotropy at trans-GZK

Correlation of the arrival directions of UHECRs with known astrophysical objects

- First search in 1995 with 143 events of energy more than $2 \times 10^{19}$ eV detected by Haverah Park array + Vulcano Ranch + Yakutsk and some preliminary AGASA data
  - Angular distance between the arrival directions and the SGP
  - Energy $> 4 \times 10^{19}$ eV, the average and RMS distances of UHECRs to the SGP are much closer to those expected by an isotropic distribution of sources.

- Increase of AGASA statistics that dominate at the end of the 1990s, event clustering were found: 3 pairs and a triple of events coming within 2.5°.

- Correlation of the Auger events with the AGNs
Anisotropy at trans-GZK

Correlation of the arrival directions of UHECRs with AGNs

Rev. Mod. Phys, 83, 907-942 (2011)
Remaining problems

Controversial results:

• **Anisotropy at highest energies:** Given the differences between the anisotropy analyses done by HiRes and Auger and the fact HiRes sees half of the Auger field of view it is not clear whether the two results are in conflict.

• **Composition:** The controversial result on the chemical composition of UHECRs is the main unsolved problem since it affects the interpretation of the end of the cosmic ray spectrum:
  - if dominated by protons (HiRes), we see the GZK effect
  - if heavier, we see the maximum acceleration rigidity at the sources

Currently, data from Auger and HiRes appear contradictory and no model is able to explain in a coherent way all the observations
New techniques

Needs:
• Covering the whole sky
• Increase the statistics by instrumenting larger surface or volumes
• Improving the measurements adding new detector components

Next generation of detectors:
• They will be able to measure independently (and redundantly) all extensive air shower components:
  • EM shower profile with a $X_{\text{max}}$ resolution of few tens of g/cm$^2$
  • Muonic and EM component at the ground level

With these measurements we will be able to constrain hadronic models and the first interaction dynamics
Current knowledge...

\( X_{\text{max}} \) for composition studies

**HiRes**: heavy at \( 10^{17} \) eV and becomes light at \( 10^{18} \) eV and continues light with a proton fraction from 60-80% above \( 10^{18} \) eV

**Auger**: light at \( 10^{18.25} \) eV and becomes heavier with increasing energy. Linear decrease of the RMS is not consistent with a simple change of the cosmic ray composition from pure proton to pure iron.
General picture

Fluorescence from the space

Radio MHz

Surface detectors

Microwave detectors

Microwave detectors

Fluorescence detectors

Fluorescence from the space
Japanese Exploration Module – Extreme Universe Space Observatory

- First space observatory devoted to UHECRs
- Privileged location at 400 km of height
- Large field of view
- Innovative optics
- High efficiency focal surface
- Unprecedented exposure at extreme energies > $10^6 \text{ km}^2 \text{ sr yr}$

- To be launched ~ 2015

**Goal:** Study cosmic rays above $5 \times 10^{19} \text{ eV}$ as well very high energy neutrinos
JEM–EUSO

- Wide angle (± 30°) camera with a diameter of 2.5 m
- UV light is imaged through Fresnel lens optics
- Focal surface detector: multi-anode PMT
- Angular resolution ~ 2.5°
- Surface covered in the Earth ~ 160,000 km²
- Duty cycle ~ 10°
- Two operation modes:
  - looking straight down
  - tilted mode (increase area by a factor 5)

Also:
- devices to measure the transparency of the atmosphere and existence of clouds
**VHE Radio emission**

**Coherent Geosynchroton Radiation**
Extensive air showers induced by cosmic rays produce secondary particles that emit a detectable electric field in the MHz range (electron-positron pairs gyrating in the Earth’s magnetic field)

**Detection principle:**
- Geomagnetic deflection of electrons and positrons
- MHz frequency range
- $\mu$V/m range amplitude
- Few ns duration

**Radio measurements of EAS:**
- Direct view into the shower development
- 100% duty cycle
- Detection threshold $\sim 10^{17}$ eV
LOPES
Low-Frequency Array Prototype Station

Located @ Kascade-Grande experiment
Array of dipole antennas
30 Lofar antennas
Kascade provides coincidence trigger

Charge particles in the shower are deflected by the geomagnetic field
CODALEMA
COsmic Detection Array with Logarithmic ElectroMagnetic Antennas

Located @ Nançay
144 decametric antennas (80 x 80 m$^2$)
24 dipole antennas (2 arms of 600 m)
17 surface detectors (340 x 340 m$^2$)

Charge particles in the shower are deflected by the geomagnetic field

+q towards E
–q towards W

Geomagnetic field direction
Radio prototypes @ Auger

Why radio in Auger?
• Extension of energy range well above $10^{18}$ eV
• Merging information from 3 independent detectors should help to precise shower characteristics and nature of the primary
• Access to very large areas (mandatory to gain statistics)
• The radio sky is very good in the site

Events from the SD

Events seen by radio

Evidence of the geomagnetic field in the electric field emission (threshold effect)
AERA
Auger Engineering Radio Array

- Realize a large scale Radio detector
- Understand the details of the radio emission processes
- Explore the potential of the radio detection technique
- Realize combined detection of air showers at Auger “Super-Hybrid“: Radio + SD + FD
Microwave emission

Molecular Bremsstrahlung Radiation (MBR)
The weakly ionized plasma created in the atmosphere after the passage of the EAS gives rise to the emission of continuous radiation (MBR) as free electrons scatter of neutral nitrogen molecules


MBR in weakly ionized plasma

• Free electrons accelerating through collisions with the fields of molecules
• Emission from < 10 eV electrons (assumed thermal)
• Expected to be isotropic and unpolarized in clear contrast to the highly anisotropic and polarized geo-synchrotron emission
• Radio emission continues 1 – 10 GHz

See Edivaldo’s talk – 08/06/11 16h45 (room 16)
Laboratory measurements

28 GeV electron beam which collided with a target of 90% Al₂O₃ and 10 SiO₂ to make showers with varying particle number.

See Edivaldo’s talk – 08/06/11 16h45 (room 16)
Scaling to air showers

Relative integrated energy in the tail of the microwave emission for 15–30 ns

\[ P \propto N_e^2 \] (coherent emission)
\[ P \propto N_e \] (incoherent emission)

Using experimental data from SLAC measurements:

- antenna effective area: 0.05 m\(^2\)
- equivalent energy shower of \(\sim 4 \times 10^{17}\) eV
- equivalent shower at distance of 10 km

**Linear scaling:** \( E_{\text{th}} = 8 \times 10^{18} \) eV

**Quadratic scaling:** \( E_{\text{th}} = 1.6 \times 10^{18} \) eV

3 \(10^{19}\) eV shower can be detected @ 20 km
AMBER
Air-shower Microwave Bremsstrahlung Experimental Radiometer

- 2.4 m low-emissivity off-axis parabolic dish
- look angle of 30°
- 4 dual-polarization feeds
- dual-band: C-band: 3.4–4.2 GHz
  Ku-band: 10.95 – 14.5 GHz

AMBER system
operated at University of Hawaii from Jan to Jun 2010
now @ Auger Observatory

Goal: observe cosmic ray showers in coincidence with surface detectors of the Pierre Auger Observatory without self-triggering
CROME
Cosmic-Ray Observation by Microwave Emission

Segmented parabolic 335 cm dish
focal length: 119 cm
prime focus with 4 receivers:
  dual linear polarization
  LNB Norsat 8215F C-band L 3.4 – 4.2 GHz
  15 K noise temperature, gain 60 dB
vertical orientation

Goal: verify the idea of microwave emission from extensive air showers

Unique opportunity to use KASCADE-Grande cosmic-ray data
MIDAS
Microwave Detection of Air Shower

MIDAS is an R&D effort to detect EAS in the microwave band due to MBR
Prototype detector @ UChicago was designed to make an FD-like detection and reconstruction of the shower

- Camera with 53 C-band feeds
  Frequency 3.4 – 4.2 GHz
  13 K noise
  70 dB amplification
- Feed central on the focus
- 4.5 m diameter parabolic dish

FOV: 10° × 20°
MIDAS

MIDAS is an R&D effort to detect EAS in the microwave band due to MBR

\[ T_{\text{sys}} \approx 120 K \]

Sun passing over the central feed

Full MC simulation

Linear scaling

1 – 2 events / month

See Edivaldo’s talk – 08/06/11 16h45 (room 16)
Posters 450 (Elvis) and 451 (André) – 08/06/11

Tuesday, June 12, 12
EASIER
Extensive Air Showers Identification with Electron Radiometers

Detection principles:
• Detection of the radio emission of the EM cascade
• Two possible bands: VHF (30 – 80 MHz) and C-band (3.4 – 4.2 GHz)
• Sensor integrated in the Auger surface array (trigger & timing from DAQ)

Observables:
• Signal proportional to the EM energy
• Time shape related to the cascade evolution and $X_{\text{max}}$
• Muonic signal in the surface detector by subtraction ($S_\mu$)

~ 100% duty cycle telescope with the coverage of a surface detector
VHE – First test hexagon

VHE (30 – 80 MHz)
Geosynchroton emission
Installed in March 2011

\[ S \text{ [dBm/10 KHz]} \]

- Viera
- Juan
VHE: First event

400 m to the core
GHz – First test hexagon

Microwave (3.4 – 4.2 GHz)
Installed in April 2011

Ongoing analysis
Calibration, noise level
Signal search
Summary

For the **UHECR studies** we need to:

- **Increase the statistics** by instrumenting larger surface or volumes
- **Improving the measurements** adding new detector components

For that the **next generation of detectors** should be able to **measure independently (and redundantly)** all extensive air shower components:

- **EM shower profile** with a $X_{\text{max}}$ resolution of few tens of g/cm$^2$
- **Muonic and EM component** at the ground level

Multiple **detector prototypes** are currently under construction at different Observatories (mainly Auger) to attempt to observe **VHE radio and/or microwave emission** from cosmic ray showers:

- VHE radio technique is **very promising**
- Current efforts on microwave detection will soon determine whether or not this detection technique is viable
Current knowledge...

Spectral features:
Acceleration or propagation effects?

Flux suppression > 20 σ

Galactic → Extra-galactic

2° knee

knee

ankle
Current knowledge...

Several models can fit the spectrum
Mass composition measurement required!