Cosmic rays at highest energies: Scientific objectives, status and plans for the future

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- Astrophysical motivation
- Pierre Auger Project and EUSO
  - Experimental concept
  - Status
  - Results
- Summary and outlook
Science Objectives

Fundamental questions

- Primaries of energies $>10^{20}$ eV exist
  Standard astrophysical models cannot account for such energies

- Complication ($d > 20$ Mpc):
  GZK cutoff $E > 5 \times 10^{19}$ eV
  
  \[ p + \gamma_{2.7K} \rightarrow \Lambda^+ (1232) \rightarrow p + \pi^0 \rightarrow p\gamma\gamma \rightarrow n + \pi^+ \rightarrow pe^+\nu \]

- If no GZK:
  - Nearby sources:
    GUT fossils (TD, DM, ...)
  - Propagation effects:
    violation of Lorentz invariance, Z-Bursts, ...

- Near sources should be identified by point source astronomy
  High magnetic rigidity of the primaries (charged particle astronomy)

Contradicting measurements

1 particle per km$^2$ and century

Newest HIRES stereo data give even more contradicting results
(W. Springer et al.; ICRC05)
1. Cosmic ray spectrum above $10^{19}$ eV: Shape of the spectrum in the region of the GZK cutoff

2. Arrival direction distribution: Search for departure from isotropy, point sources

3. Composition: Light or heavy nuclei, photons, neutrinos, exotics(?)
Study of GZK-Cutoff Requires Much Higher Statistics

Different source distributions

source distribution following star-formation
uniform $E^{-2.75}$
source distributions
The Pierre Auger Project

A new cosmic ray observatory designed for a high statistics study of the
The Highest Energy Cosmic Rays
Using
Two Large Air Shower Detectors

Colorado, USA
(in planning)

Mendoza, Argentina
(Auger South)
The Auger Collaboration

Participating Countries

Argentina  
Australia  
Bolivia*  
Brazil  
Czech Republic  
France  
Germany  
• Aachen  
• Bonn  
• Karlsruhe  
• Siegen  
• Wuppertal  

Mexico  
Netherlands  
Poland  
Slovenia  
Spain  
United Kingdom  
USA  
Vietnam*  
Italy

*Associate

63 Institutions, 369 Collaborators
The Hybrid Design

Surface detector array + Air fluorescence detectors
A unique and powerful design

Nearly calorimetric energy calibration of the fluorescence detector transferred to the event gathering power of the surface array.

A complementary set of mass sensitive shower parameters (Xmax, risetime, radius of curvature, ...).

Different measurement techniques help understanding of systematic uncertainties

Improve of the angular and core position resolutions
Hybrid Design

Surface Array
- 1600 detector stations (995)
- 1.5 km spacing
- 3000 km²

Fluorescence Detectors
- 4 Telescope enclosures (3)
- 6 Telescopes per enclosure
- 24 Telescopes total (18)
Design Features

1. High statistics (aperture >7000 km² sr above $10^{19}$ eV in each hemisphere)

2. Full sky coverage (S&N) with uniform exposure

3. Hybrid configuration surface array with fluorescence detector coverage

Thanks to Kai Daumiller for this movie!
The Surface Array
Detector Station

- Communications antenna
- GPS antenna
- Electronics enclosure
- Solar panels
- Battery box
- 3 – nine inch photomultiplier tubes
- Plastic tank with 12 tons of water
Surface Detector Deployment
The Fluorescence Detector

- 3.4 meter diameter segmented mirror
- 440 pixel camera
- Aperture stop and optical filter
The Fluorescence Detector Stations

- **Los Leones** *(fully operational)*
- **Coihueco** *(fully operational)*
- **Morados** *(fully operational)*
- **Lomo Amarilla** *(in preparation)*

*poor mans fall back option :-)*

K.-H. Kampert
Atmospheric Monitoring and Calibration

Atmospheric Monitoring

- Central Laser Facility
- Lidar at each fluorescence eye
- Atmospheric radio sounding measurements

Absolute Calibration

- Drum for uniform camera illumination: end to end calibration
Example Event (48°, E~70 EeV)
Horizontal Showers

$E \approx 5 \cdot 10^{19} \text{ eV} \quad \theta = 82^\circ$
Horizontal Showers and Neutrinos

$E > 10^{18} \text{ eV}$

Only neutrinos can produce such signatures

Neutrino rate $\sim 0.5 - 1 \text{ particle / year}$

Depends strongly on the theoretical model
Cosmogenic Neutrino-Flux and Experimental Sensitivities

Semikoz, Sigl, astro-ph 0309328
Stereo Hybrid Measurement

Event: 1364365

Los Morados

Los Leones

Ig(E/eV)~19.3
(\(\theta,\phi\)= (63.7, 148.3) deg)

Ig(E/eV)~19.2
(\(\theta,\phi\)= (63.7, 148.4) deg)

Ig(E/eV)~19.1
(\(\theta,\phi\)= (63.3, 148.9) deg)
Stereo Hybrid Event: SD-Measurement

Event: 1364365

Event: 1364365
Time: 00:33:36 16 MAY 2005
GPS Time: 800238829 s, 31974000 ns
T4: FD+STOT+4C1 T5: Yes
Reconstruction stage: 4,1
Easting: 479996. ± 35.7 [m]
Northing: 6082011. ± 13.5 [m]
θ: 63.3 ± 0.3 [°]
ψ: 148.9 ± 0.3 [°]
R: 19.6 ± 0.05 [km]
S: 32. ± 1.2 [VEM]
β: -1.71 ± 0.04
Triocular Event

\[ \lg(E/eV) \sim 19.7 \]
\[ \theta = 52^\circ \]
Performance: Angular Resolution

Hybrid Angular resolution
(68% CL)
0.6 degrees (mean)

Surface array Angular resolution (68% CL)
< 2.2° for 3 station events (E < 3EeV, θ < 60°)
< 1.7° for 4 station events (3 < E < 10 EeV)
< 1.4° for 5 or more station events (E > 10 EeV)
Performance: Core Resolution

Laser Data
- Entries 168
- Monocular: Mean -271 m, RMS 566 m
- Hybrid: Mean 27 m, RMS 57 m

Hybrid Data
- Entries 501
- Mean 5.8 ± 6.5 m, RMS 147 m
- Mean 68 ± 8 m, RMS 173 m

Laser position – Hybrid and FD only (m)
- Hybrid: < 60 m
- Surface array: ~150 m

Hybrid – SD only core position
- Early
- Late

Core position resolution
- Hybrid: < 60 m
- Surface array: ~150 m
The First Data Set

Collection period:
1 January 2004 to 5 June 2005

Zenith angles:
0 - 60°

Total acceptance:
AUGER: ~1750 km² sr yr ~ AGASA
HIRES I: ~5000 km² sr yr (mono)
HIRES II: ~2500 km² sr yr (mono)

Surface array events (after quality cuts):
Current rate: ~18,000 / month
Total: ~180,000

Hybrid events (after quality cuts):
Current rate: ~1,800 / month
Total: ~18,000
Anisotropy: Galactic Center

Coverage [0.8-3.2 EeV]
Significance (3.7°)

Coverage [0.8-2.5 EeV]
Significance (13.3°)

excess flux
AGASA: 4.5 \( \sigma \)
Sugar: 2.9 \( \sigma \)

\( \Phi_s < 10.6 \times 10^{-15} \text{ m}^{-2} \text{ s}^{-1} \)
excludes neutron source at the GC
Photon Limit

Hybrid events: improved geometry fit

Selection criteria:
• $E > 10^{19}\text{eV}, \quad \theta > 35^\circ$
• $X_{\text{max}}$ observed, track length > 400 g/cm$^2$
• Energy dependent distance cut

16 Events after cuts

26% upper limit (95% CL) on CR photon fraction
Energy Determination (Conversion)

The energy converter:

Compare ground parameter $S(1000, \text{at } 38^\circ)$ with the fluorescence detector energy (CIC method)

Transfer the energy converter to the surface array only for events

$$\log (E) = -0.79 + 1.06 \log (S_{38})$$

$$E = 0.16 S_{38}^{1.06}$$

$(E \text{ in EeV}, S_{38} \text{ in VEM})$
Auger Energy Spectrum

\[ \frac{dI}{d \ln(E)} \equiv E \frac{dI}{dE} \quad \text{vs.} \quad \text{Lg}(E) \]

Error bars on points indicate Poisson statistical uncertainty (or 95% CL upper limit) based on the number of events.

Systematic uncertainty is indicated by double arrows at two different energies.

Horizontal: Systematic \( \Delta E \).

Vertical: Exposure uncertainty.

\[ \frac{x^2}{dof} = 2.4 \]
A Big Event - *One that got away!*

Energy estimate $>140$ EeV
Comparison with HIRES, AGASA

AUGER: Energy scale uncertainty still large
~50 % at 100 EeV
Plans for Auger North

Needed: Full sky coverage

Colorado, USA has been selected as the northern site

Funding proposals to be prepared over the next two years.
EUSO Science Goals

• Detection and investigation of the Extreme Energy Component of the Cosmic Radiation: EECRs / UHECRs with E > 5×10^{19} eV

• Arrival directions and small-scale clustering will provide information on the origin of the EECRs and inter-galactic magnetic fields.

• Open the Channel of High Energy Neutrino Astronomy to probe the boundaries of the Extreme Universe and to investigate the nature and distribution of the EECR sources

• ...

Extreme Universe Space Observatory
EUSO Consortium - Institutes

>150 researchers in 50 institutions in 6 countries in Europe, the USA, Japan and Brazil.

**Participant Nations and Institutions**

- **Brazil**
  - IAG, Univ Sao Paulo
- **France**
  - APC, Paris
  - CDF, Paris
  - IAP, Paris
  - LPSC, Grenoble
  - LPTHE, Paris
  - OdP, Paris
- **Italy**
  - MPIfIP, Munich
  - MPIHLL, Munich
  - MPIfRA, Bonn
  - Univ. Wuerzburg
  - EKU Tübingen
- **Germany**
  - LIP, Lisbon
- **Portugal**
  - IAA-CSIC, Granada
  - Dpt.FTC & CAFPE, Univ. Granada
- **Spain**
  - Obs. Neuchatel
- **Switzerland**
  - MSFC & NSSTC, Huntsville
  - UAH, Huntsville
  - UCB, Berkeley
  - UCLA, Los Angeles
  - Vanderbilt Univ.
- **USA**
  - RIKEN
  - ICRRR
  - Konan Univ.
  - ISAS
  - Rikkyo
  - KEK
  - NAO
  - Tokyo Univ.
  - Saytama
  - Aoyama
  - Kinki
  - Seikei
  - Kanazawa
- **Japan**
  - MPIfP, Munich
  - MPIHLL, Munich
  - MPIfRA, Bonn
  - Univ. Wuerzburg
  - EKU Tübingen

- **Brazil**
  - IASF, Palermo
  - ISAC-CNR, Bologna
  - INFN & Univ. Genova
  - INFN & Univ. Firenze
  - INFN & Univ. Torino
  - INFN & Univ. Trieste
  - INFN Catania & Univ. Palermo
  - Univ. Roma “La Sapienza”
  - Scuola Normale Sup. Pisa
  - Oss. Astrofisico Arcetri
  - Oss. Astrofisico Catania
  - CARSO
  - INOA
The Why’s of a space-based detector for EECR

• Geometrical Factor \((A \cdot \Omega)\) (FoV=±30° at ISS mean distance \(h_{\text{ISS}}\approx 430\text{km}\))

\[
A^{\text{geo}} \approx 6 \times 10^5 \text{ km}^2 \cdot \text{sr}
\]

\[
\eta_{\text{cycle}} \approx 10 \div 25 \%
\]

\[
A^{\text{eff}}_{\text{Euso}} \approx (6 \div 9) \times 10^4 \text{ km}^2 \cdot \text{sr}
\]

• Full Sky Coverage

• Cerenkov “footprint” of shower

The EUSO observational goal:

~ 1000 events/a in SuperGZK mode
> 70 events/a in GZK-suppressed mode
Scientific Requirements:

- High statistics \implies large aperture

- Energy threshold as low as possible to allow a dynamical range overlap and cross-calibration with ground array (AUGER) \implies high sensitivity to faint showers, bkg. Rejection

- Pointing capability \implies direction resolution

Instrumental Requirements:

- Large aperture \implies FoV as large as possible
  \(\pm 30^\circ\) \implies \sim 6 \times 10^5 \text{km}^2 \text{sr from ISS mean orbit height}

- Sensitivity \implies High luminosity
  \((2.5 \text{m} \varnothing \text{collecting area, } 5 \text{mm} \varnothing \text{PSF, } f\#<1.15, \text{Q.E.}>0.2 \implies \sim 50\% \text{ efficiency at } 5 \times 10^{19} \text{eV}, 100\% \text{ efficiency at } 10^{20} \text{ eV})\)

- Primary direction resolution \iff space resolution in FoV, time resolution
  \((0.1^\circ \text{ angular resolution, } 2.5 \mu \text{s time resolution } \implies \pm 1^\circ \text{ on EECR incoming direction})\)
Integrated Aperture
EUSO – The Instrument
How to detect EECRs from space

STEP 1
Particle penetrating Earth’s atmosphere creates an EAS. UV fluorescence light is produced along the particle trajectory and it is imaged by the EUSO telescope.

STEP 2
Highly collimated Cherenkov photons are also produced in the forward direction of EAS. At the impact point with the earth surface, reflected/diffused UV light is imaged by the telescope.

STEP 3
Instantaneous IR picture of the FOV is taken at trigger occurrence.

STEP 4
Sounding of the atmosphere, along the EAS direction, is performed by a LIDAR system.
The signal registered by EUSO

The EUSO telescope

The signal arriving on EUSO

Shower appear as single track event (embedded in the bg)

Duration, X,Y, Intensity, $\Theta, \phi, E, A$ of the EECR/$\nu$.

The space-time image is given in terms of X-T and Y-T projections of the collected photoelectrons, X and Y being the coordinates inside the field-of-view; the time coordinate T measures the shower development in depth, providing info about the shower length in the third direction, the height in the atmosphere.
Downward neutrino acceptance for EUSO

2 * 10^{18} \text{g} \text{ is the total target mass under the FOV}

reduction due to trigger efficiency calculated by full simulation. Clouds distribution is considered

reduction due to selection efficiency needed for 10^{-4} proton rejection calculated from full simulation

results show a sensitivity around 10 \times \text{AUGER} for neutrino in the 10^{20}\text{eV} energy region
Summary: EUSO

- EUSO is a pioneering experiment studying EAS from space:
  - An instantaneous aperture of $6 \times 10^6 \text{km}^2\text{sr}$ with a duty cycle $\sim 20\%$ is a technically achievable goal with up-to-date technology;
  - The acceptance reduction due to cloud effect has been evaluated to be $\sim 1/3$.

- EUSO, with its dynamical range ($E > 5 \times 10^{19} \text{eV}$) is a “beyond-GZK experiment”. At $E > 10^{20} \text{eV}$:
  - $\sim 10^3$ events/year can be expected according to AGASA findings;
  - $\sim 10^2$ events/year can be expected according to GZK-suppressed spectrum due to uniform source distribution.

- EUSO complement the AUGER findings in both cases:
  - Study the source spectra for superGZK model;
  - Analyse the GZK behaviour and the source distribution for GZK-suppressed mode;

- EUSO highly sensitive to neutrino astronomy at $E > 5 \times 10^{19} \text{eV}$
But …

- EUSO on the ESA module Columbus is uncertain due to ISS/Shuttle delays
- Phase A completed, technically ready for phase B (15 July 2004)
- EAS unable to recommend its continuation into phase B in foreseeable future (AWG, FPAG, SSAC)

⇒ Freezer status

- EUSO will be supported on “exciting” Auger results;

Alternative Solution?
- EUSO mounted on the Japanese Module
- Using a Japanese carrier to launch EUSO
- ? …
Effective Aperture
50-100 times Auger
10 times EUSO

Energy threshold close to $10^{18}$ eV

Cf. Günther Hasinger‘s talk: Status, Probleme und Perspektiven
Summary and Outlook: Pierre Auger Observatory

Status:
- Southern Observatory over half finished
- With 25% of a full Auger-year exposure, we have:
  - First estimate of an FD-calibrated spectrum
  - First studies of anisotropies in the sky
  - Limits on photon primaries

Future plans:
- Completion by mid 2006
- Full understanding of our instruments
- Usage of rapidly expanding data set (x7 in two years)
- Measure spectrum around $10^{20}\text{eV}$ with unprecedented precision
- Solve AGASA/HIRES dispute
- Composition studies with SD, FD and HYBRID
- Large/small scale anisotropies
- Search for neutrinos and exotics (horizontal showers)
- Begin working on Auger North
- R&D for radio, ...