Highlights* of Astrophysical Observations from the Pierre Auger Observatory
(*more details at the ICRC 2011, Beijing, 11-18 Aug, and on the ArXiv on Tuesday)

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Outline

I. The Pierre Auger Observatory

II. From EAS observables to UHECR parameters: reconstruction and resolutions

- Primary Flux and Spectrum
- Primary Composition
- Arrival direction distributions

IV. Summary
Galactic Magnetic Field can contain CRs up to $10^{17}-10^{18}$ eV: UHECRs are expected to be extragalactic: where is the “transition”? 2nd knee? ankle?

At the “end” of the spectrum: flux cutoff expected due to extragalactic CR interactions on CMB photons (GZK effect)

UHECRs are expected to come from “close” sources (GZK horizon, < 200 Mpc) and to be marginally deflected by magnetic fields: CR astronomy possible

Last but not least: center of mass energy larger than that of LHC
Prologue: inferences on UHECR ($E > 10^{18}$ eV)

Flux so low ($\approx 1/{\text{km}^2 \text{ y}}$) that only indirect measurements are possible, through Extensive Air Showers (EAS)

UHECR parameters (direction, energy and mass) can be inferred from various EAS observables (particle distribution at ground, longitudinal profile, arrival times, EAS shape etc...)

The “conversion” from EAS to UHECR may require the use of hadronic interaction models

The study of the energy spectrum AND distribution of arrival directions AND mass composition are the key ones to infer astrophysical informations on UHECR nature AND origin AND propagation

A schematic view of CR spectrum
I. The Pierre Auger Observatory
The Pierre Auger Observatory: a “hybrid” instrument

- “Hybrid” detector: 1600 water Cherenkov (SD) + 4x6 fluorescence detectors (FD)
- SD fully efficient above 3 EeV (100% d.c.), FD&SD above 1 EeV (but ≈ 13% d.c.)
- In operation from 2004 (completed in 2008)
- Full Auger: ≈ 1500 (100) (2) events/month above $3 \times 10^{18} (10^{19}) (5 \times 10^{19})$ eV
Auger extension to lower energies: **AMIGA and HEAT**

- "Hybrid" detector: **61 (+24)** water Cherenkov (Infill) + **3** fluorescence detectors (Heat)
- Infill fully efficient above **0.3 EeV** (**100% d.c**), Heat&&Infill above **0.1 EeV** (but ≈ **13% d.c.**)
- 53/61 infill stations now in operation. Heat fully operating.
- Nominal Infill: ≈ **700 (20) (4)** events/month above **3x 10^{17} (10^{18}) (3x 10^{18}) eV**
Auger extension to new detection techniques: AERA

- Foreseen layout: 160 antennas over 20 km² (spacing 250-350 m)
- Currently: 21 150 m spaced antennas (since Sept 2010)
- Aim: “FD-like” detector (EAS longitudinal development), but with > 90% d.c.
- Energy threshold: \( \approx 10^{17} \text{ eV} \)
- First cosmic-ray events presented @ ICRC 2011
II. From EAS observables to UHECR parameters: reconstruction & resolutions
From EAS particles arrival times to UHECR arrival direction

CR arrival direction: from relative arrival times of signals at ground detectors

Auger Angular resolution: estimated on an event-by-event basis. Verified with hybrid events

Angular resolution over 7 years of data: stable within 0.1°

$E > 10^{18}$ eV ($>10^{19}$ eV): $\geq 3$ (6) tanks: < 2° (1°)

$E > 10^{18}$ eV ($>10^{19}$ eV): $\geq 3$ (6) tanks: < 2° (1°)
From EAS particles lateral and longitudinal distribution towards primary CR energy

SD measures the lateral distribution (LDF) of EAS particle at ground

FD measures the EAS longitudinal development in atmosphere

Event # 787469
38 triggered tanks
Zenith angle ~ 60°
Preliminary energy estimate ~ 10^{20} eV

Energy estimator = signal @ 1000 m from impact
.small shower-to-shower fluctuations, depends on primary E only
From LDF -> S(1000)
Accuracy: 14%

FD: calorimetric measurement:
E \approx \text{area “under” the curve}
Accuracy: \approx 8%
From SD energy estimator & FD energy to primary CR energy

Hybrid Events are used to calibrate the SD energy estimator, \( S(1000) \) [converted to the median zenith angle, \( S_{38} \)] with the FD calorimetric energy.

Statistical uncertainty on \( E_{SD} \): \( \approx 15\% \)

Total systematic uncertainty on energy scale \( \approx 22\% \) (main contribution: fluorescence yield)

Energy resolution over 7 years of data: stable within 5%
From EAS longitudinal profile to primary CR identification in FD

**X_{max}, depth of EAS maximum, is the main EAS observable sensitive to CR mass**

First interaction of heavy primaries is shallower and fluctuates less. \( \text{RMS}(X_{\text{max}}) \) mass sensitive too

**EAS development observed by FD:**

\( \text{X}_{\text{max}} \) accuracy \( \approx 20 \text{ g/cm}^2 \) (by “stereo” events)

\( \sigma \approx 20 \text{ g/cm}^2 \)

\( \sigma/E \approx 8\% \)

N.B.: the “correspondence” \( \text{XMAX} \)-\( \text{mass} \) depends on extrapolations of hadronic models at UHE!
NEUTRINOS: from “age” of horizontal showers

PHOTONS: from EAS structure
- smaller radius of curvature of the shower front

SIGNAL RISE TIME
- larger time spread and longer signal risetime

HADRONS: from time structure of EAS signal
- e.g.: Muon production depth distribution

Garcia-Gamez et al, ICRC 2011 $X^{[g \text{ cm}^2]}$

NEUTRINOS: from “age” of horizontal showers

OLD SHOWERS ($h$)
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

YOUNG SHOWERS ($\nu$)
- Wide time distribution
- Strong curvature
- Steep lateral distribution

“Slow & broad signal”

“Fast & narrow signal”
III. Astrophysical observations:

- Energy spectrum
- Distribution of arrival directions
- Nature of primary particles
UHECR energy spectrum: Auger SD and hybrid events

**SD exposure:** 20905 km² sr y, 60% more than in PLB 685 (2010) 239

**Hybrid exposure:** doubled wrt PLB 2010

Very good agreement between SD and hybrid
Flux within 2% wrt our previous measurement

Salamida et al, ICRC 2011
Model-independent measurement and analysis

**Observation of an “ankle” at \( \approx 4 \times 10^{18} \) eV and a suppression at \( 4 \times 10^{19} \) eV**

Ankle: transition galactic to extra-galactic CRs? Composition and anisotropy mea. needed

Suppression: GZK or source limits? Composition and anisotropy mea. needed

*N.B. Extension down to \( 0.3 \times 10^{18} \) eV to be presented at ICRC 2011 (Maris et al)*
Cosmogenic (GZK) photons and neutrinos?

- Search for photons and neutrinos relevant \textit{wrt} UHECR production and propagation (GZK)

- UHECR source models:
  
  (a) Bottom-Up: UHECR are accelerated in astrophysical sources
  
  (b) Top-Down: UHECR are produced in the decay of supermassive relic particles from Big Bang, topological defects, monopoles etc.: high fluxes of photons and neutrinos are predicted

- No neutrinos nor photons observed with Auger: GZK photons and neutrinos within reach in Auger livetime (10 y)

- TD models mostly excluded: astrophysical sources favoured

\textit{Guardincerri et al, ICRC 2011}

\textit{Settimo et al, ICRC 2011}

\textbf{Neutrinos}

\textbf{Photons}

\textbf{Single flavour neutrino limits (90\% CL)}

\textbf{Neutrinos}

\textbf{Photons}

\textbf{Integral Flux E}\textsubscript{E0} [km\textsuperscript{2} sr\textsuperscript{-1} yr\textsuperscript{-1}]

\textbf{upper limits 95\% C.L.}

\textbf{Hybrid 2003}

\textbf{Hybrid this work}

\textbf{Hyperbolic SD}

\textbf{GZK}
UHECR arrival directions: two lines of study in Auger

At \( \approx 50 \text{ EeV}: \) Small scale anisotropies
- The distance from which a source can contribute to the flux @ earth is limited ("GZK-Horizon")
- Processes that produce UHECR require special conditions: few astrophysical objects are candidate
- Inhomogeneities in their spatial distribution may imprint anisotropy
- Comparison of UHECR arrival directions with astronomical objects is a tool for source identification

At \( \text{EeV}: \) Large scale anisotropies
- Study of the evolution of anisotropy vs energy to possibly identify the transition from galactic to extra-galactic component
- If CRs below the ankle galactic: sidereal modulations observable due to escape from the galaxy (% level, depending on GMF)
- If CRs below the ankle extra-galactic: sidereal modulations observable due to cosmological Compton-Getting effect

Astrop. Ph. 34 (2010) 314
Astrop. Ph. 29 (2008) 188
Science 318 (2007) 938

Astrop. Ph. 34 (2011) 627
Update at ICRC 2011 (Lyberis et al)
Auger UHECR arrival directions: small-scale anisotropies

27 CR above 56 EeV (Jan 2004-31 Aug 2007) ->
correlation with the positions of nearby quasars and AGNs (12th VCV)

Correlation at: energy (55 EeV), angular separation (3.1°), distance (75 Mpc) fixed with early data
Test with later data, built to reject isotropy with 1% probability of doing it incorrectly: test passed
(9/13 correlated events): --> **Isotropy rejected at 99% c.l.**
Updated estimate of the degree of correlation (69 events above 55 EeV, up to Dec 2009)

**Correlation decreased from (69±12)% to (38±7)% (21/55 correlated events)**

Fraction expected under isotropic hypothesis: 21%

Cumulative binomial probability P=0.003
Search for correlations with alternative populations of extra-galactic objects 
(2MRS galaxies and Swift-BAT AGNs: more homogeneous and complete than VCV)

Statistical test of the 69 events with density maps weighting each object by their flux and distance (GZK effect). Two free parameters: smoothing angle \( \sigma \) (deflection) and isotropic fraction \( f_{iso} \) (incompleteness, heavier elements...), obtained from best fit to data

Best fit: 2MRS \( \rightarrow (1.5^\circ, 64\%) \); Swift \( \rightarrow (7.8^\circ, 56\%) \).

Large isotropic fraction favoured
Auger UHECR arrival directions: large-scale anisotropies

- First harmonic analysis in right ascension (Rayleigh formalism)
  - Correction for atmospheric effects on EAS and non-uniform exposure in sidereal time
  - Applied to energy > 1 EeV
- East-West analysis
  - Based on counting rates differences between E and W directions: atmospheric and instrumental effects automatically removed
  - Applied to E<1 EeV

No significant amplitude is found at any energy
An interesting change in phase is observed at \( \approx \) the “ankle” energy (posterior probability: 0.002). Need test with independent (future) data
Auger UHECR arrival directions: large-scale anisotropies

Galactic models (A,S,Gal): anisotropy by CR motions (drift or diffusion) due to the (regular or turbulent) component of the GMF

Some of the predicted amplitudes are challenged by Auger current sensitivity

Model C-GXgal: Compton-Getting anisotropy due to motion of our galaxy wrt the CMB. Within reach in Auger lifetime
Change of elongation rate \( \frac{d<X_{\text{max}}>/d\log E} \) at \( \log_{10}(E)=18.38 \), i.e. close to the ankle
Slow increase of \(<X_{\text{max}}>\) with energy

Fast decrease of RMS\((X_{\text{max}})\) with energy

Caveat: Interpretation in terms of mass is model-dependent. Within current models:
Possible change in composition (from light to heavier) in the ankle region
Trend towards heavier composition for increasing energies
Any departure from predictions from current models (e.g. Allen et al ICRC 2011) would alter conclusions on mass composition
Auger EAS longitudinal development and CR mass from SD

SD EAS observables of longitudinal development: profile of muon production points and asymmetry of signal risetime

Comparing SD data with models, similar conclusions can be drawn as from FD data on Xmax

Same caveat holding on the models validity
The Pierre Auger Observatory is taking data in stable mode: annual increase of fiducial exposure $\approx 6000$ km$^2$ sr. Data from 3.5 “Auger-years” accumulated: at least 7 more to come!

Flux suppression observed at $\approx 4 \times 10^{19}$ eV, compatible with GZK cutoff. An “ankle” observed at $\approx 4 \times 10^{18}$ eV.

Stringent upper limits on photons and neutrinos: top-down models disfavoured, astrophysical UHECR sources favoured.

UHECR arrival directions above GZK energy: anisotropic and correlated with nearby matter distribution.

Large scale anisotropy in the EeV energy region: no evidence in amplitude ($\approx 1\%$). But suggestion of a smooth phase transition above the “ankle”. Test with independent future data.

EAS longitudinal development compared to UHE extrapolation of hadronic models: trend to heavier composition with $E$.

(N.B. current models at variance with muon Auger data, see Engel’s talk on Wed 27 Aug).

The Pierre Auger Observatory is currently extended into a multi-hybrid detector, that will operate at energies below the ankle too.

Future UHE ground EAS arrays are planned in a world-wide effort (workshop to be held at the beginning of 2012 - 100th birthday of CR discovery ;-)
Backup
Comparison between Auger and HiRes spectra

Energy shift of 25% applied to Auger data
HiRes: correlation with VCV (same Auger parameters):
2/13 correlated events (3.2 expected by chance)
2/13 not incompatible with 38% Auger correlation

Moreover, correlation may be different in the two emisphere (AGN distribution and different incompleteness of the VCV catalogue)

Challenging cross-check due to “different” energies (very steep spectrum)
Auger Xmax distributions
Auger Xmax distributions: shape ($<X_{\text{max}}<$ subtracted)

At low energies: consistent proton component

At high energies: significant fraction of nuclei (CNO or heavier)
\( \langle X_{\text{max}} \rangle \): Better statistics and precision (stereo and hybrid data) (but still important differences in the models).

Discrepant results (in spite of apparent agreement within systematic errors):

- Constant elongation rate from HiRes
- Change of elongation rate at the ankle from Auger
RMS(Xmax): Even more discrepant results

Constant rms from HiRes (Suggesting Protons)

Decrease of rms from Auger (suggesting increasing average mass)

N.B. Different data treatment: HiRes RMS from gaussian fit truncated at 2 RMS, no correction for detector resolution; Auger: no truncation, correction for detector resolution
Search for the largest excess (above 57 EeV):

12 events in a 13° cell (1.7 expected): It lies at 4° from CEN A

Centering on CEN A: largest excess within 18° (13 events vs 3.2 expected)

Interesting sky region to be monitored

Auger UHECR arrival directions: small-scale anisotropies