Measurement of the energy spectrum of cosmic rays using the Pierre Auger Observatory

Denise Boncioli

Università di Roma Tor Vergata

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The Pierre Auger Observatory - Malargüe, Argentina

Surface Detector (SD)
- 1600 water Cherenkov detectors
- 1.5 km standard grid
- total area $\sim 3000 \text{ km}^2$

Fluorescence Detector (FD)
- 27 fluorescence telescopes
- 4+1 buildings at the periphery
The cosmic ray energy spectrum

- Due to the total SD area, the PAO can measure the UHECR spectrum up to $E \sim 10^{20}$ eV with good statistics.
- Due to the detector spacing, the PAO can measure the UHECR spectrum down to $E \sim 10^{18}$ eV.
- Recently "low energy" enhancements extend event measurements down to $10^{17}$ eV.
Two complementary techniques to detect Extensive Air Showers

**Surface Detector**
- 100% duty cycle
- Energy threshold $3 \times 10^{18}$ eV

**Fluorescence Detector**
- $\sim 13\%$ duty cycle
- Energy threshold $\sim 10^{18}$ eV
Two complementary techniques to detect Extensive Air Showers

**Surface Detector**
- 100% duty cycle
- energy threshold $3 \times 10^{18}$ eV

**Fluorescence Detector**
- $\sim 13\%$ duty cycle
- energy threshold $\sim 10^{18}$ eV

- signal recorded by SD: correlated to the primary particle at a fixed distance from the core
- timing info: EAS axis

- profile of energy deposit of the shower ⇒ primary energy and composition
- EAS geometry determination

**SD energy calibration with FD**

![Diagram](image-url)
Two complementary techniques to detect Extensive Air Showers

Surface Detector

- 100% duty cycle
- Energy threshold $3 \times 10^{18} \text{ eV}$

Fluorescence Detector

- ~13% duty cycle
- Energy threshold $\sim 10^{18} \text{ eV}$

- Profile of energy deposit of the shower
  ⇒ primary energy and composition
- EAS geometry determination

SD energy calibration with FD
Event selection

- zenith angle $< 60^\circ$
- $E > 10^{18.4}$ eV

Statistics

- Jan 2004 - Dec 2010
- $\mathcal{E} = 20905$ km$^2$ sr yr

64000 (5000) events above 3 EeV (10 EeV)
Hybrid spectrum

Hybrid events: sub-sample of EAS recorded by both the FD and the SD, used to relate the energy reconstructed with the FD to the SD energy estimator

⇒ energy scale applied to all showers detected by the SD array.

Statistics

- Nov 2005 - Sep 2010
- exposure
  → taking into account the changing configurations of both FD and SD.

Main systematic uncertainty: energy assignment
  - knowledge of fluorescence yield
  - “invisible energy”

→ 22% total uncertainty on the energy scale
Auger "low energy" enhancements

Auger towards $10^{17}$ eV

- 750 m infill SD stations
  $\mathcal{E} = 26 \text{ km}^2 \text{ sr yr}$

extends the energy range down to $3 \times 10^{17}$ eV

very good agreement with the combined spectrum

with FD enhancements (HEAT): improvement on energy calibration at low energies
Combined spectrum

Energy spectrum derived from hybrid data combined with the one obtained from surface detector data

- SD energy estimator: calibrated with hybrid events $\Rightarrow$ 22% uncertainty on the energy scale
Combined spectrum

\[ E^3 J(E) \text{ [km}^2 \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}] \]

\[ \log_{10}(E/eV) \]

\[ \gamma_1 = 3.27 \pm 0.02 \quad \gamma_2 = 2.68 \pm 0.01 \quad \log_{10}(E_{\text{break}}/eV) = 19.41 \pm 0.02 \]

\[ \gamma_3 = 4.2 \pm 0.1 \]

→ by fitting the flux with a broken power law

- position of the ankle: \[ \log_{10}(E_{\text{ankle}}/eV) = 18.61 \]
- suppression of the flux: \[ \log_{10}(E_{1/2}/eV) = 19.41 \]
Features of the spectrum - Flux suppression

Possible interpretations of the suppression:

- **suppression due to PROPAGATION**
- → CR interactions with the photon background

If **protons** → photopion production process

A proton with $E_{\text{inj}} = 10^{21}$ eV produced beyond $\sim 100$ Mpc reaches the Earth with $E_{\text{det}} < 10^{20}$ eV.

**Greisen-Zatsepin-Kuzmin effect**

If **nuclei** → photodisintegration process

An iron with $E_{\text{inj}} = 10^{21}$ eV produced beyond $\sim 100$ Mpc doesn’t reach the Earth...

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Different processes involving different particles but same effect on the energy spectrum
Possible interpretations of the suppression:

- suppression due to **PROPAGATION**
- → CR interactions with the photon background

As an example, in the case of protons:
Features of the spectrum - Flux suppression

Possible interpretations of the suppression:

- **suppression due to PROPAGATION** → CR interactions with the photon background

- **suppression due to PROPERTIES of SOURCES** → maximum energy of acceleration of CR in the source

- different scenarios (also a combination of them) could explain the flux suppression

- scenarios involving unknown parameters
  - $E_{max}$
  - composition
  - distribution of sources

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Models

Spectrum fitted with different compositions

F. Schüssler for the PAC, ICRC 2009
A better agreement requires no proton dominated composition
A better agreement requires no proton dominated composition

⇒ many possible scenarios involving mixed composition
Auger composition results

- Composition observable: atmospheric depth at which the shower attains its maximum size carries information about mass of the primary particle
- Evidence of change of composition from light to heavy
- Independent confirmation from other composition indicators

P. Facal for the PAC, ICRC 2011
Combining results...

Reproduce experimental spectrum with models with **no proton dominated** composition.

Spectra obtained with *SimProp*, a simulation code for the propagation of nuclei in extragalactic photon backgrounds

- developed by DB, A. Grillo, S. Petrera, F. Salamida

\[
E \left[ \text{eV} \times \text{cm}^2 \times \text{sr}^{-1} \text{yr}^{-1} \right] = 10^{16} \text{ for } 18 \leq \log_{10}(E/\text{eV}) \leq 18.5 \\
10^{17} \text{ for } 18.5 \leq \log_{10}(E/\text{eV}) \leq 19 \\
10^{18} \text{ for } 19 \leq \log_{10}(E/\text{eV}) \leq 19.5 \\
10^{18.5} \text{ for } 19.5 \leq \log_{10}(E/\text{eV}) \leq 20 \\
10^{19} \text{ for } 20 \leq \log_{10}(E/\text{eV}) \leq 20.5
\]

- no Iron cutoff
- Iron cutoff 20.5

\[17 < \log_{10}(E/\text{eV}) < 22.5, 0 < z < 3, \gamma = 2.4\]

- in this case the energy cutoff has no influence on the all-particle spectrum...
- but it affects the presence of protons at high energies ⇒ important parameter for correlations?
Conclusions

- Updated measurement of the cosmic ray flux with the Pierre Auger Observatory
- Two independent methods (SD and Hybrid) have been used, deriving a combined spectrum
- **Measurement of ankle and flux suppression** at highest energies

- Independent composition observables: evidence of change of composition from light to heavy

- No good fit of Auger spectrum found for proton dominated composition
- Models involving heavy source composition and propagation of nuclei in intergalactic photon backgrounds are under study to understand implications on the energy spectrum

**Source Models** = source hypothesis (injection spectrum + composition + source distribution) + propagation code + shower development code

→ the energy spectrum alone cannot discriminate among different source scenarios

- A global view on results about UHECR (energy spectrum + composition + correlations) can help to limit the source scenarios compatible with data