Overview of Galactic Cosmic Ray Detection

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Outline

- Introduction

- Selected science results on galactic cosmic rays
  - all-particle energy spectrum
  - elemental composition
  - energy spectra based on different hadronic models

- Extensive air shower measurements of PeV to EeV
  - knee and transition region:
    KASCADE, KASCADE-Grande, Tunka, IceTop
  - TA Low Energy Extension: TALE
  - Auger to lower energy: HEAT

- Conclusion
Galactic Cosmic Rays

Acceleration of cosmic rays in supernova remnants

Propagation through galaxy ($B=3\mu G$)

Direct or indirect measurement
The knee around $3 \times 10^{15}$ eV
- A second knee above $10^{17}$ eV
- A dip just below $10^{19}$ eV
- A GZK feature above $10^{19}$ eV
Motivation for Measurements of PeV to EeV:
- Overlap direct-indirect measurements?
- Rigidity dependent knee?
- Elemental composition at knee?
- Transition galactic to extragalactic origin of CR?
Present Experiments $10^{16} - 10^{18}$ eV

- KASCADE-Grande
- IceTop (IceCube)
- Auger - HEAT
- TA - TALE
- Tunka
Measurement Techniques of Air Showers

KASCADE-Grande
IceTop
Tunka
HEAT, TALE

First interaction (usually several 10 km high)
Air shower evolves (particles are created and most of them later stop or decay)
Some of the particles reach the ground
Measurement of fluorescence light
Measurement with scintillation counters
Measurement of low energy muons with scintillation or tracking detectors
Measurement of high energy muons deep underground

Measurement of Cherenkov light with telescopes or wide angle pmts
Measurement of particles with tracking detectors or calorimeters
KArlsruhe Shower Core and Array DETector

- Energy range 100TeV – 80PeV
- Since 1995
- Large number of observables
KASCADE Energy Spectra of Single Mass Groups

Searched: energy and mass of the cosmic ray particles
Given: \( N_e \) and \( N_\mu \) for each single event \( \rightarrow \) solve the inverse problem

\[
\frac{dJ}{d \lg N_e d \lg N_\mu} = \sum_A \int_{-\infty}^{+\infty} dJ_A \frac{p_A(\lg N_e, \lg N_\mu | \lg E) d \lg E}{d \lg E}
\]

- Knee caused by light primaries
- Relative abundancies depend strongly on high energy interaction model

Kernel function obtained by Monte Carlo simulations (CORSIKA)
Contains: shower fluctuations, efficiencies, reconstruction resolution
KCDC (KASCADE Cosmic ray Data Centre) = publishing research data from the KASCADE experiment

Motivation and Idea of Open Data:
- general public has to be able to access and use the data
- the data has to be preserved for future generations

Web portal:
- providing a modern software solution for publishing KASCADE data for a general audience
- In a second step: release the software as Open Source for free use by other experiments

Data access:
1.6\cdot10^8 EAS events of first data release is now available

Paper in preparation

https://kcdc.ikp.kit.edu/
KASCADE-Grande
(KARlsruhe Shower Core and Array DEtector + Grande)

- Total effective area: 0.5 km²
- Large array of 37 stations with 137m spacing
- Each station has a plastic scintillation detector of 10 m²
- 18 trigger clusters (0.5Hz)
Energy and Elemental Composition

- 2-dim. shower size distribution → determination of primary energy
- Separation in “electron-rich” and “electron-poor” events

\[
\log_{10}(E) = \left[a_p + (a_{Fe} - a_p) \cdot k\right] \cdot \log_{10}(N_{ch}) + b_p + (b_{Fe} - b_p) \cdot k
\]

\[
k = \frac{(\log_{10}(N_{ch}/N_\mu) - \log_{10}(N_{ch}/N_\mu)_p)}{(\log_{10}(N_{ch}/N_\mu)_{Fe} - \log_{10}(N_{ch}/N_\mu)_p)}
\]
Spectra of Individual Mass Groups

- steepening close to $10^{17}$eV (2.1$\sigma$) in all-particle spectrum
- steepening due to heavy primaries (3.5$\sigma$)
- hardening at $10^{17.08}$eV (5.8$\sigma$) in light spectrum
- Slope change from $\gamma = -3.25$ to $\gamma = -2.79$
Structures of all-particle, heavy and light spectra similar → knee by heavy component; ankle by light component

Relative abundances different for different high-energy hadronic interaction models
Combined Analysis

- For KASCADE: additional stations at larger distances $\rightarrow$ higher energies
- For Grande: additional 252 stations $\rightarrow$ higher accuracy
Energy spectra based on different hadronic interaction models
All structures confirmed
All-particle spectrum good agreement
Relative abundance of light and heavy quite different

Spectra not corrected for uncertainties
Combined Analysis: QGSJet-II.04 vs EPOS-LHC

- Light primary interactions okay?
- Heavy primary interactions show differences

Muon component not sufficiently described
(Distance from shower core covered by muon detectors limited)
Attenuation length measured is different from the predictions of Monte Carlo

→ Observed evolution of the muon content of EAS in the atmosphere is not described by the hadronic interaction models

→ Influences absolute energy and mass scale, but not spectral features

[Juan Carlos Arteaga, Submitted to Astropart. Phys.]
Conclusion Combined Analysis

- Structures of spectra confirmed
- Models still do not agree to each other and to data
- Light component seems to agree better than heavy
- Problem probably in the muons (known due to special selection)
- Around $10^{15}$ eV still (again) no clear picture

[Dissertation of Sven Schoo, Paper in preparation]
Energy range: 100 TeV – 1 EeV
Area: >1 km²; 675 m a.s.l.
Cherenkov-experiment: LDF
2011: Tunka-133 is extended by 6 distant external clusters
Tunka: Reconstruction

- Core accuracy $\sim 10$ m
- Energy resolution $\sim 15\%$
- Energy threshold at $10^{15}$ eV

- $E_0 \sim (Q_{200})^g$ (LDF function, $g$ depends on composition)
- $X_{\text{max}}$ reconstruction: Steepness of LDF
Two sharp feature at energies:
- $2 \cdot 10^{16}$ eV (first announced by KASCADE-Grande in 2010)
- $3 \cdot 10^{17}$ eV (similar to that announced by Yakutsk and Fly’s Eye in 90th)

Tunka-HiSCORE:
- prototype 9 optical stations
- 80 h during 13 clean moonless nights from February to March in 2014

[V. Prosin et al, EPJ Conf. 121 (2016) 03004]
Tunka: Comparison With Others

- Agreement with KASCADE-Grande and IceTop

- All the spectra coincide with Tunka-133, if energy of KASCADE-Grande is increased by 3% and energy of IceTop is decreased by 3%

- This shift is less than announced experimental accuracy

- Agreement with old Fly’s Eye, HiRes and TA spectra
- The heavy component (all other) has a break at $10^{17}$ eV
- The light component (p+He) starts to rise again above $10^{17}$ eV
An agreement with previous Auger 2013

But no enough statistics to discuss the discrepancy with the current Auger results
- Energy range: PeV – 1 EeV
- Area: 1 km²
- 2835m altitude (680 g/cm²)
- 81 ice cherenkov stations
- LDF + particle density at 125m
- In-ice high-energy muons
The spectrum does not follow a simple power law above the knee up to 1 EeV.

- Observed a spectral hardening at $18 \pm 2$ PeV.
- The spectrum steepens at $130 \pm 30$ PeV.
- Coincident event analysis uses a neural network to determine both energy and composition.
- Improvements in snow attenuation calculation and in light propagation models.

Systematic error band showed corresponds to 7% composition systematic.

Energy dependence of $\langle \ln(A) \rangle$ from the coincident analysis and its systematic effects

The combined IceTop+IceCube analysis shows a clear trend toward heavy primaries in average $\langle \ln(A) \rangle$

The heavy knee is at higher energies and above the models
Same structures observed in spite of different observables and observation levels

Absolute scale difference: < 20% within systematics (by method and composition sensitivity)
10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

Graded infill surface detector array - more densely packed surface detectors (lower energy threshold)
Combined TA Energy Spectrum

- TALE FD \( (10^{16.5} < E < 10^{18.4} \text{ eV}) \)
- TALE FD reconstructed using only the Cherenkov light \( (10^{15.6} < E < 10^{17.4} \text{ eV}) \)
- Two features: a low energy ankle at \( 10^{16.34} \text{ eV} \) and a second knee at \( 10^{17.3} \text{ eV} \)
Comparison With Others

- Strong composition dependence and still large systematic errors
- Discrepancy between TA Combined and the ground based experiments due to systematic effects?
High Elevation Auger Telescope (HEAT)

- Low energy extension of Pierre Auger Observatory
- 3 tiltable FD at Coihueco site with FOV of 30 – 60° in upward mode
- Due to the FOV higher in the atmosphere, sensitive down to $10^{17}$eV → on decade in energy overlap with KASCADE-Grande

Auger Muons and Infill for the Ground Array (AMIGA):
SD Infill + Muon Counter
23.5 km² with 750 m spacing
HEAT: Composition

- Energy range: $10^{17} - 10^{18.3}$ eV
- Data between 01.06.2010 and 15.08.2012
- Mean of the shower maxima as well as their fluctuations indicate a composition becoming lighter up to $10^{18.3}$ eV
- Transition from light to heavier primaries above $10^{18.3}$ eV
Features of the energy spectrum found by KASCADE-Grande have been confirmed by Tunka, IceTop and TALE with improved statistics and analysis technique:

- A steepening at $10^{17}$ eV dominated by heavy components
- A hardening at about $2 \cdot 10^{16}$ eV
- A flattening of the light component around $10^{17}$ eV = Maybe the first sign of an extra-galactic component

The mass composition of KASCADE-Grande, Tunka and IceTop shows similar tendencies, however, the absolute scale difference is still large due to hadronic interaction models:

- Still some contradiction on the composition around $10^{18}$ eV
- HEAT indicates a clear transition from heavy to light between $10^{17}$ eV and $10^{18}$ eV, while Tunka and IceTop show a less pronounced effect.

Relative abundancies depend strongly on high energy interaction model and astrophysical interpretation is limited by description of interactions in the atmosphere. Need to improve the hadronic interaction models