Cosmic Rays from knee to ankle: knowledge and open questions

Andreas Haungs
High-energy cosmic ray spectrum

Equivalent c.m. energy $s_{pp}$ (GeV)

Air-shower measurements

Knee(s), transition galactic-extragalactic

Low energy CR measurements (balloon or satellite)

Highest energy cosmic rays

Scaled flux $E^{2.5} J(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{-1.5}$)

Energy (eV/particle)

HERA (e+e-), RHIC (p+p), Tevatron (p+p), LHC (p+p)
Cosmic Rays: 1958

The “first knee”

G.V.Kulikov & G.B.Khristicsen

Soviet Physics JETP  Volume 35(8), No 3,  March 1959

measured $N_{ch}$ spectra

hodoscope counters

in a 20x20 m² array

„the observed spectrum is a superposition of the spectra of particles of galactic and metagalactic origin“
Galactic cosmic rays

Acceleration of cosmic rays in supernova remnants

Propagation through galaxy ($B \approx 3 \mu G$?)

Direct or indirect measurement

Affirmation by H.E.S.S.
Nature 531, 476 (2016)
Questions to the knee-to-ankle energy range

Overlap direct-indirect measurements?
Hadronic interaction models?
Rigidity dependent knee?
Fine-structures in spectrum?
Composition at knee?
Spectra of individual masses?
Iron knee?
End of Galactic Spectrum?
Second knee?
Transition galactic – xgalactic?
Anisotropy?

Engel, Blümer, Hörandel: Progress in Particle and Nuclear Physics 63 (2009) 293
Extensive Air Showers - schematic

EAS measurement and reconstruction:
- energy ?
- mass ?
- arrival directions ?
- interaction mechanism ?

~10%  ~ 1%  ~90%
KASCADE
KArlsruhe Shower Core and Array DEtector

- Energy range 100TeV – 80PeV
- Since 1995
- Large number of observables: electrons, muons@4 thresholds, hadrons

KASCADE timeline

- 57 collaborative papers in reviewed journals (3-4 still in queue, short author list papers not included)
- 56 PhD thesis
- 86 diploma/master thesis

Muon production height

Proof-of-principle radio detection

(an)isotropy

γ limit

Light knee

Model tests

KASCADE-Grande

EAS GHz emission

Light ankle

Heavy knee

Xmax by radio

KCDC

CROME

Karlsruhe Air Shower Test Facility

Cosmic Revelation

• 57 collaborative papers in reviewed journals (3-4 still in queue, short author list papers not included)
• 56 PhD thesis
• 86 diploma/master thesis

KASCADE

CORSIKA

Proposal

Andreas Haungs
CORSIKA (COsmic Ray SImulations for KAscade)

>2000 citations

New Initiative: modernized CORSIKA as community effort (2018++)

> 1 day per $10^{15}$ eV shower

< 20 min per $10^{15}$ eV shower

700 users from 50 countries and 50 experiments

LHC adapted Models
Parallelization
Radio: CoREAS

ECRS 2018, Barnaul, Russia
Andreas Haungs
KASCADE: energy spectra of single mass groups

Searched:
E and A of the Cosmic Ray Particles

Given:
\(N_e\) and \(N_\mu\) for each single event

\(\Rightarrow\) solve the inverse problem

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

- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution

KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25
KASCADE: the rigidity knee

- same unfolding but based on different hadronic interaction models embedded in CORSIKA

- all-particle spectrum similar
- general structure similar: knee by light component
- relative abundances very different for different high-energy hadronic interaction models but for many models: proton not the most dominant component!

Validity of Hadronic Interaction Models

First, high energy interaction: LHC + multiparameter measurements EAS

Secondary interactions: Fix target experiments + multiparameter measurements EAS
Charged particle distribution in pseudorapidity

Protons: $E_{\text{lab}} = 3 \times 10^{16} \text{ eV}$

Post LHC models
Protons: $E_{\text{lab}} = 8 \times 10^{18} \text{ eV}$

(data from all LHC experiments, CMS shown as example)

D‘Enterria, Pierog, JHEP 08 (2016) 170
KASCADE : sensitivity to hadronic interaction models

correlation of observables:

no hadronic interaction model describes data consistently !

→ tests and tuning of hadronic interaction models !

→ close co-operation with theoreticians (CORSIKA including interaction models)

→ e.g.:
  • EPOS 1.6 is not compatible with KASCADE measurements
  • QGSJET 01 and SIBYLL 2.1 still most compatible models

Result KASCADE ➔ Motivation KASCADE-Grande

Flux $E^{2.5} J(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{-1.5}$)

- PROTON
- RUNJOB
- direct data

Motivation KASCADE-Grande
- KASCADE (QGSJET 01)
- KASCADE H
- KASCADE He
- KASCADE heavy
- KASCADE (SIBYLL 2.1)
- KASCADE H
- KASCADE He
- KASCADE heavy

Proton data

Energy (eV/particle)

- KASCADE
- Grande
- Pierre Auger Observatory
- Energy range: 100TeV – 1EeV
- Area: 0.5 km²
- Grande: 37×10 m² plastic scintillation detectors
- Nch + total muon number

2-dimensional shower size spectrum

- determination of primary energy
- separation in “electron-rich” and “electron-poor” event

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

\[
k = \left( \log_{10}(N_{ch}/N_{\mu}) - \log_{10}(N_{ch}/N_{\mu})_p \right) / \left( \log_{10}(N_{ch}/N_{\mu})_{Fe} - \log_{10}(N_{ch}/N_{\mu})_p \right)
\]
KASCADE-Grande
energy spectra of
mass groups

- steepening due to heavy primaries (3.5σ)
- hardening at $10^{17.08}$ eV (5.8σ) in light spectrum
- slope change from $\gamma = -3.25$ to $\gamma = -2.79$

Phys.Rev.D (R) 87 (2013) 081101
KASCADE-Grande: model dependence

- Spectra of heavy primary induced events
  - a knee structure at the heavy component
  - relative abundances different for different high-energy hadronic interaction models
• for KASCADE: additional stations at larger distances ➔ higher energies

• for Grande: additional 252 stations ➔ higher accuracy

Sven Schoo, KIT, PhD 2016
KASCADE-Grande: Combined Analysis resulting energy spectra (post-LHC hadronic interaction models)

all structures confirmed

Spectra not corrected for uncertainties

Sven Schoo, KIT, PhD 2016
KASCADE-Grande: Combined Analysis
resulting energy spectra based on hadronic interaction models

- Post LHC models
  light primary interactions okay?
  heavy primary interactions show differences

QGSJet-II.04 vs. EPOS-LHC vs. SIBYLL 2.3
KASCADE-Grande: combined analysis
Check Hadronic Interaction Models

- assume a composition model: H4a by Tom Gaisser
- two selections: core located in KASCADE, core located in Grande
  → we measure “different” muons
**KASCADE-Grande: Combined Analysis**

**Test of models**

- **One model, but two selections:**
  - Simulations okay, but strong differences in data
  (similar result for QGSJet-II.04, EPOS-LHC, SIBYLL 2.3)

- ➔ **Muon component not sufficiently described**
Results

- Structures of spectra identified (light and heavy knees, light ankle)
- Astrophysical (H4a, e.g.) model not far away from real composition
- Hadronic 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

All particle, light and heavy induced spectra for 3 orders of magnitude!

Paper in preparation
Analysis by Sven Schoo
Light and Heavy Knees, Ankles, and Transition

Hillas model

KASCADE-Grande confirms rigidity dependent knees (A component)

(galactic) B-component needed to explain all-particle spectrum

Highest energy extragalactic (Auger)

Anisotropy in arrival direction?

Light and Heavy Knees, Ankles, and Transition

Maximum acceleration model for extragalactic component

Slope of proton in the model same as slope of “light” spectrum after ankle in KASCADE-Grande

IceCube PeV neutrinos from 100 PeV extragalactic protons?

Measured PeV-neutrinos by IceCube

⇒ cosmic neutrinos from IceCube correspond to \(10^{17}\) eV protons
Limits on diffuse Gamma-ray Flux
Multimessenger Analysis

- selection of muon-poor events

- limits on ratio of primary gammas to hadrons

- limits on diffuse Gamma-ray flux constrain the origin of IceCube-neutrinos

\[ \Rightarrow \text{Reject the model of IceCube excess coming from } <20\text{kpc in the Galaxy} \]
Measurement Techniques of Air Showers

energy ?
mass ?
arrival directions ?
interaction mechanism ?

- 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 with radio emission
- Measurement of fluorescence light
- Measurement of Cherenkov light with telescopes or wide angle pmts
- Measurement with scintillation counters
- Measurement of high energy muons deep underground
- Measurement of low energy muons with scintillation or tracking detectors
- Measurement of particles with tracking detectors or calorimeters
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 low energy muons with scintillation or tracking detectors

Measurement with scintillation counters

Measurement of radio emission

Measurement of fluorescence light

Measurement of Cherenkov light with telescopes or wide angle pmts

Measurement of particles with tracking detectors or calorimeters

Measurement of high energy muons deep underground
Tunka-133 ➔ TAIGA

- Energy range: 100 TeV – 1 EeV
- Area: >1 km²; 675m asl
- Cherenkov-experiment: LDF
- 2011: Tunka-133 is extended by 6 distant external clusters

light flux at core distance 200 m \[ Q_{200} \sim \text{Energy} \]

steepness of LDF \[ P = \frac{Q(100)}{Q(200)} \Rightarrow X_{\text{max}} \]

IceTop ➔ Enhancements / IceCube-Gen2

- Energy range: PeV – 1EeV
- Area: 1 km²
- 2835m altitude (680 g/cm²)
- 81 ice cherenkov stations
- LDF + particle density at 125m
- in-ice high-energy muons

Phys Rev D (2013) accepted - dx.doi.org/10.1016/j.asr.2013.05.008
Structures of all-particle spectra similar (in the level of 15%) - first composition results are in agreement with KASCADE-Grande.
UHECR experiments

Pierre Auger Observatory ➔ HEAT/AMIGA/AERA

TALE Spectrum compared to some recent Measurements

- TALE Monocular (2017)
- Yakutsk Cherenkov (2013)
- Tunka-55 (2013)
- Tunka-133 (2013)
- KASCADE-Grande (2012)
- ICETOP (2016)
IceTop+IceCube: Composition

- 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

• The **heavy component** (N+Fe) has a break at $10^{17}$ eV, reaching a fraction value of 80%
• The **light component** starts to rise again above $10^{17}$ eV
• Up to now we cannot confirm the sharp decrease of $\langle \ln A \rangle$ seen by KASCADE and the high $\langle \ln A \rangle$ at $10^{17}$ eV

S. Epimakhov
Tunka-133 (2015)
A lot of (promising) progress in $X_{\text{max}}$ determination by radio Experiments

- published already by LOPES
  - PhysRevD 90(2014)062001
  - Tunka-Rex
    - PRD 97, 122004 (2018)
  - LOFAR
    - Nature 531(2016)70

- Auger/AERA promising
  - Higher energy
  - More accurate EAS
  - Calibration
  - Various methods

➔ Interpretation debatable: “Unless, contrary to current expectations, the extragalactic component of cosmic rays contributes substantially to the total flux below $10^{17.5}$ eV, our measurements indicate the existence of an additional galactic component to account for the light composition we measured…..” (LOFAR@Nature)
NEVOD-DECOR experimental complex

NEVOD
9 x 9 x 26 m³ volume;
91 QSM; 546 PMT

Nevod/Decor

DECOR
8-layer supermodules (SM) of streamer tubes. Accuracy about 1 cm and better than 1°.

Kokoulin, ICRC 2017
Nevod/Decor: Measurement of muon bundles at different zenith angles

- $\theta \geq 55^\circ \Rightarrow$ practically pure muons remain
- Observed increase of energy deposit with zenith angle
- In reasonable agreement with simulations, except the region between $65^\circ - 75^\circ$ ($10^{17} \sim 10^{18}$ eV).

$\Rightarrow$ For a fixed zenith angle interval, energy deposit is correlated with primary energy

Simulations show a tendency to a slow decrease of muon energy in the bundles with the increase of primary energy.

In contrast, data indicate some increase of the average specific energy deposit at high muon densities (corresponding to effective primary energies more than $10^{17}$ eV).

Kokoulin, ICRC 2017
experiments in the knee energy range

• **(Tibet, ARGO) LHAASO**
  CR around knee with multi-detector installation
  China - with participation of France, Italy

• **TAIGA/ Tunka/HiSCORE/Tunka-Taiga-Rex**
  CR around knee and up to ankle with multi-detector installation
  Russia - with participation of Germany, more?

• **IceCube/IceTop – (Gen2)**
  Ice-Cherenkov array on top of IceCube
  USA – with important European contribution
  Advanced plans for Gen2-surface (veto) array

• **GRAPES**
  KASCADE-like operating array at 2300m altitude
  India - with participation from Japan

• **HAWC**
  High-Altitude Gamma-ray Observatory in Mexico
  Extension with outer trigger for better CR detector

• **NEVOD**
  Nevod / Decor complex now with air shower array
Nevod / Decor
IceCube / IceTop (-Gen2)
https://kcdc.ikp.kit.edu
• KCDC = 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: Version NABOO is released (Feb.2017) 4.3·10^8 EAS events are available including energy deposits corresponding simulations ~100 spectra of EAS experiments

https://kcdc.ikp.kit.edu/

German-Russian Project: Astroparticle Data Life Cycle Initiative

• Basics
  • project period 2018-2020
  • funded by Helmholtz and RSF
  • Team leaders: A. Kryukov (SINP MSU) and A. Haungs + A. Streit (KIT)

• Main targets of the Project
  • Extension example: data from Tunka/TAIGA and KASCADE-Grande
  • Developing solutions of distributed data storage techniques with a common meta-catalog
  • Development of appropriate machine-learning techniques
  • Perform experiment overarching multi-messenger astroparticle physics
  • Learn to use GridKa environment
  • Creation of an educational subsystem

Open PhD positions!
Contact me.... 😊
Motivation:
- Astroparticle Physics requests for multi-messenger analyses.
- This needs an experiment-overarching platform
- High demand in (German and international) community
- APP Observatories are globally distributed (no CERN or ESA)

Important steps:
- Develop an open science system (based on KCDC and the LHC-Tier environments)
- Develop solutions of distributed data storage algorithms and techniques
- Allowing community to perform multi-messenger analyses with deep learning methods
- Providing platform for public access to scientific data
Conclusions – open points

- Light and heavy knee established
- Light ankle probably there
- Difficult to compare experiments due to different observables, what is contribution of MHz-Radio?
- Yet no conclusive result due to insufficient hadronic interaction models
- Continuation in improving hadronic interaction models required
- Still problem: absolute mass scale
- Confrontation of the data with astrophysical models still challenging
- Future: (mass dependent) Anisotropy studies
- Future: Multi-messenger Analyses (cosmic rays, \(\gamma\)-rays, neutrinos)
- IceTop(-Gen2), TAIGA, LHAASO, GRAPES, TALE, PAO, NEVOD, HAWC?
- Global Data Centre for Astroparticle Physics envisaged
CR from Knee to ankle: Contribution to most important question!

Cosmic Rays? Nobody knows where they come from.

Still a better understanding of extensive air showers by improved hadronic interaction models are needed to answer this question.

Hopefully not another 106 years (since V.Hess) or even 25 years (since KASCADE) needed to finally answer this question.