Air Shower Measurements from PeV to EeV

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Cosmic Rays around the knee(s)

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

Scaled flux $E^{-2.5} J(E)$ [$m^{-2} \text{sec}^{-1} \text{sr}^{-1} \text{eV}^{-1}$]

Energy (eV/particle)

- PROTON
- RUNJOB
- KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- MSU
- Akeno
- HiRes-MIA
- HiRes I
- HiRes II
- AGASA

fixed target (p-A)

HERA ($\gamma$-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
LHC (C-C)

Ralph Engel, 2004

August 2006 – TeV workshop Madison, US

Andreas Haungs
Astrophysical questions for this energy range:

• **(1\text{st}) knee**
  – Knee position
  – Composition at the knee
  – Anisotropy around the knee
  – Structure of spectrum (below, around, and above the knee)
  – End of the galactic cosmic ray spectrum?

• **2\text{nd} knee, dip, ankle**
  – Transition to extragalactic CRs?
  – The iron knee?
  – Anisotropies, Point Sources?
What is the origin of the knee?

Various theories:

1. **Diffusion**
   - Escape from our Galaxy by diffusion
   - $E(\text{knee}) \sim Z$

2. **Acceleration**
   - Reach of maximum energy at the acceleration
   - $E(\text{knee}) \sim Z$

3. **Interaction**
   - Unknown effects of interactions at the air-shower development
   - $E(\text{knee}) \sim A$
What is the origin of the knee(s)?
Experimental situation 2004: energy spectrum

[Jörg Hörandel, 2004]
What is the origin of the knee(s)?
Experimental situation 2004: composition

Experimental challenge:
- Convolution of energy
- mass
- arrival directions
- interaction mechanism

- large number of observables
- hybrid measurements
- multi-detector systems

In this review: only measurements with combined spectra and composition analysis (individual spectra)
Measurement Techniques of Air Showers

- 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 scintillation counters
- Measurement of radio emission
- 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
KASCADE : multi-parameter measurements

- energy range 100 TeV – 80 PeV
- up to 2003: $4 \cdot 10^7$ EAS triggers
- large number of observables:
  - electrons
  - muons (@ 4 threshold energies)
  - hadrons
Suggestion A.Watson
(Summary ISVHECRI 2006):
basic observable analysis first

\[ N(\rho_\mu^*) \, (\rho_\mu^*)^{2/3} \, [m^{-2} \cdot s^{-1} \cdot sr^{-1} \cdot m^{-2/3}] \]

\[ <R_c> = 45.5 \text{ m} \]

- "all" EAS
- "electron-rich" EAS
- "electron-poor" EAS

\[ E_\mu^{th} = 2.4 \text{ GeV} \]

- KNEE CAUSED BY DECREASING FLUX OF LIGHT ELEMENTS
- Do we need hadronic interaction models?
KASCADE : energy spectra of single mass groups

Measurement:
KASCADE array data
900 days;
0-18° zenith angle
0-91m core distance
lg $N_e$ > 4.8;
lg $N_{\mu}^{\text{tr}}$ > 3.6
⇒ 685868 events

Searched:
E and A of the Cosmic Ray Particles
Given:
$N_e$ and $N_{\mu}$ for each single event
⇒ solve the inverse problem

$g(y) = \int K(y, x) p(x) dx$

with $y=(N_e, N_{\mu}^{\text{tr}})$ and $x=(E, A)$
KASCADE results

- same unfolding but based on two different interaction models:
- SIBYLL 2.1 and QGSJET01 (both with GHEISHA 2002) all embedded in CORSIKA

KASCADE results: confirmation

- Same unfolding but based on two different low energy interaction models and different zenith angle ranges:
  - GHEISHA 2002 and FLUKA (both with QGSJET01)
  - 0-18°, 18-25.9°, 25.9-32.3° (all with QGSJET01/FLUKA)

- Less dependence for unfolding based on different low energy hadronic interaction models
- Weak dependence on zenith angle (not significant)

H. Ulrich, XIV ISVHECRI, Weihai, China 2006
KASCADE result: sensitivity to hadronic interaction models

Main results keep stable independent of method or model:
- knee in data structure
- knee caused by light primaries
- positions of knee vary with primary elemental group
- no (interaction) model can describe the data consistently

Experiment: TIBET AS\(_\gamma\)

1996-1999 AS+EC+BD
AS array 36900 m\(^2\) \(\Rightarrow\) \(N_e\)
EC 80 m\(^2\) \(\Rightarrow\) families
177 events \(\Rightarrow\) p,He spectra
Neural Net analysis
Monte Carlo: assume rigidity dependent
knee at \(E=1.5 \cdot 10^{14} \cdot Z\)

Result: TIBET $A_S^\gamma$

Proton spectra match "Proton satellite" (line) ~ to RUNJOB
~ to KASCADE (Sibyll)

Helium spectra (= p+He minus p, because p and He cannot be Separated) match ~ to RUNJOB, but lower than JACCE, KASCADE (Sibyll)

Result: TIBET AS$_\gamma$

Note:
- 177 measured events in 3 years
- Efficiency corrections with factors up to $10^4$
- Claim: model independent

TIBET conclusion: composition heavy already at the knee


TIBET next: YAC array higher efficiencies to measure also heavy elements

Shibata, XIV ISVHECRI, Weihai, China 2006
Experiment: EAS-TOP

Array at Campo Imperatore
2000 m a.s.l., 820 g·cm⁻²
→ Shower size

Calorimeter
→ Muon number @180m
(E_μ > 1 GeV)
Result: EAS-TOP

Experiment: EAS-TOP+ MACRO

MACRO and EAS-TOP separated by 1100 - 1300 m of rock
($E_\mu \approx 1.3 - 1.8$ TeV)
Common angular field
$16^\circ < \theta < 58^\circ$, $127^\circ < \phi < 210^\circ$
$E_\circ \sim 100$ TeV

3830 events in coincidence (Sep. ‘98-May ‘00).

expected accidentals <2 event coinc. off-line
(GPS system - $\sigma_T < 1$ms)

Experiment: Grapes @ Ooty

Scintillation detectors: (1m$^2 \times 5$cm)
256 detectors with 8m separation
Recording timing and pulse height of charged particles

Muon detectors:
16 detectors with 6m$ \times $6m area ($E_\mu >$1GeV)
Total area of 560m$^2$
Recording the individual track of muons

Kawakumi, XIV ISVHECRI, Weihai, China 2006
Promising: Grapes @ Ooty

Muons multiplicity distribution

\[ 5 \leq \log_{10}(N_e) < 5.2 \]

- still missing: estimate of systematic uncertainties
- nice agreement with KASCADE
- results expected: ICRC 2007
Analysis of large scale anisotropy of cosmic rays:

Anisotropy: different astrophysical models for the origin of the knee can be distinguished by their predictions of anisotropy.

KASCADE collaboration

no large scale anisotropy observed limits in Rayleigh amplitude
Summary Results (first knee): Proton spectra

Comparison with direct measurements
Summary Results (first knee):

- Analysis:
  Hybrid measurements and convolution is required
  (analyzing mean values of data and simulations appears inadequate)
- Knee is due to decrease in flux in light primaries!
  (model independent; most experiments)
- How wrong are the models?
  (no new physics needed, compare proton spectrum)
- Distinguishing between astrophysical models
  (investigation of Anisotropy for different primaries)
  (help from TeV Gamma Ray Astronomy)
- Knee position dependence: $\propto Z$ or $\propto A$?
A or Z?

Data: KASCADE, H. Ulrich, XIV ISVHECRI, Weihai, China 2006
Motivation for measurements 100 – 1000 PeV

- Iron knee?
- Second knee??
- Transition galactic-extragalactic CR??

![Graph showing the flux of particles as a function of energy.](image)
Fe-knee $\sim 10^{17}$ eV
gal-eg transition $\sim 10^{17.7}$ eV
Ankle = eg characteristics

Fe-knee $\sim 10^{18}$ eV
gal-eg transition $\sim 10^{19}$ eV
= ankle

Various theories on energy range $10^{17}$-$10^{19}$ eV:

- e.g. Wibig et al, J. Phys. G 31 (2005) 255

Cannonball model:
Fe-knee $\sim 2 \times 10^{17}$ eV
All is galactic (knee = elastic scattering)
Present experimental situation: energy spectrum

HIRES claims the evidence of a second knee!

Present experimental situation: composition

HIRES/MIA claims a change of composition at the second knee!

More (higher statistics) and better (hybrid measurements) experiments needed: Convolution analysis of the data!

KASCADE-Grande: multi-parameter measurements

KASCADE + Grande
- energy range: 100 TeV – 1 EeV
- large area: 0.5 km²
- Grande: 37x10 m² scintillators
- Piccolo: trigger array
KASCADE-Grande: first analyses

- Unfolding of 2-dimensional shower size spectrum possible
- First access to the data: Combination of muon and electron number → all angular bins show same flux in energy

Still improvements in systematics needed

Glasstetter et al. – KASCADE-Grande coll., ICRC (2005) Pune, India
H. Ulrich, XIV ISVHECRI, Weihai, China 2006
Experiment: ICETOP / ICECUBE

ICETOP at Antarctica
Array of ice Cherenkov detectors
→ Shower size

ICECUBE
→ Muon number ($E_\mu > 500$ MeV)
Experiment: TALE @ TA

TA:
- $E > 10^{19}$ eV $\rightarrow \varepsilon = 100\%$
- $E > 10^{18}$ eV $\rightarrow$ hybrid

TALE:
- 6km stereo pairs (two of them) $\rightarrow$ best $@10^{18}$ eV
- 72 deg elevation tower + infill $\rightarrow E > 10^{16.5}$ eV

X. Bai, XIV ISVHECRI, Weihai, China 2006
Experiment: Auger Enhancement
FD, SD infill + muons

new FD: $E > 5 \times 10^{16}$ eV

SD infill + muon counters:
$E > 5 \times 10^{16}$ eV

K-H. Kampert, CRIS 2006, Catania, Italy
Medina et al., astro-ph/0607115
My conclusions:

• Pev to EeV physics needs (still) air-shower investigations
  • at the knee recently very sophisticated experiments and analyses

  ➔ knee is caused by light primary elements
    (KASCADE, EAS-TOP, Grapes) ➔ TIBET
  ➔ cosmic rays are isotropic around the knee

• interaction models have to be further improved (without new physics)

• knee most probable due to mixture of acceleration and propagation effects
  • possible key points: anisotropy studies for individual elements and combination with TeV-Gamma-Ray Measurements

• in near future same quality for 100-1000 PeV
  (KASCADE-Grande, ICETOP/CUBE, TALE, Auger)
  to find the „iron“-knee and transition galactic–extragalactic cosmic rays!

• new detection techniques (radio) ?

Still a Vital Field of Research