ASTROPHYSICS AROUND THE 'KNEE' OF PRIMARY COSMIC RAYS

Andreas Haungs
Forschungszentrum Karlsruhe, Germany

ISMD Krakow, September 2003

Energy per nucleus $E$ (GeV)

$\log(I(E))$ $[m^2 s^{-1} sr^{-1} eV^{-1}]$

$10^{-3}$ $10^{-5}$ $10^{-7}$ $10^{-9}$

$-35$ $-30$ $-25$ $-20$ $-15$

knee ankle
direct measurements EAS measurements

$p$ Fe

$I(E) \sim E^{-\gamma}$

$\gamma = 2.7$ $\gamma = 3$

Tevatron KASCADE Grande LHC ankle

haungs@ik.fzk.de

KASCADE-Grande collaboration
Cosmic rays

Source → Acceleration → Transport

Injection

Stellar matter

Supernovae

Spallation

Experiments
The Problem

What is the origin of the "KNEE"?

- change of the cosmic ray sources? (source, acceleration, composition)
- effect of transport mechanism? (leaking from Galaxy)
- effect of interaction of CRs in the atmosphere?

Experimental access:

- all-particle (single mass group) cosmic ray energy spectrum  
  \[ \propto Z \text{ or } \propto A \] ??
- elemental composition around the "knee"!
- anisotropy of cosmic rays around the "knee"!
- investigations of the hadronic interaction mechanisms!
Extensive Air Shower – EAS

- Primary particle
- Shower axis
- Zenith angle
- Shower disk: ~1 m
- Detector array
- Central detector

Primary Particle

- Nuclear interaction with air molecule
- Hadronic cascade
- Hadronic fragments
- Nuclear fragments
- Cerenkov radiation
- Muonic component, neutrinos
- Electromagnetic component
- Muons, p, n, K, π, γ

Detection of EAS

1. First interaction (usually several 10 km high)
2. Air shower evolves (particles are created and most of them later stop or decay)
3. Measurement of low energy muons with scintillation or tracking detectors
4. Measurement of high energy muons deep underground
5. Measurement of particles with tracking detectors or calorimeters
6. Measurement of Cherenkov light with telescopes or wide angle PMTs
7. Measurement with scintillation counters
8. Measurement of fluorescence light

Schematic views of EAS
The all-particle energy spectrum

Average values from 14 measurements ± variance:

\[ E_k = (3.2 \pm 1.2) \cdot 10^{15} \text{ eV} \]

slope below knee: \( \gamma_1 = -(2.68 \pm 0.06) \)

slope above knee: \( \gamma_2 = -(3.06 \pm 0.08) \)

flux at 1 PeV: \( (2.73 \pm 0.70) \cdot 10^{-9} \text{ m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{TeV}^{-1} \)
The elemental composition

huge spread of results – why?

mean logarithmic mass

\[ \langle \ln A \rangle \]

depth of shower maximum

- which observables?
- which Monte Carlo model?
- which method of analyses?
- sensitivity of the measurable?
- calculation of mean mass?
- energy estimation?

challenge for the experiments

motivation for the theory

A. Haungs ISMD 2003, Krakow – p.6/31
Origin of the knee??

\[ E_{\text{knee},A} \propto Z \times E_{\text{knee},p} \]

Maximum of acceleration process:

\[ E_{\text{max}} < Z \times (L \times B) \]
\[ E_{\text{max}} < Z \cdot 10^{15} \text{ eV} \]

e.g. in Supernova Remnants

Escape from our Galaxy:

\[ E_{\text{max}} < Z \cdot 3 \cdot 10^{15} \text{ eV} \]

e.g. magnetic rigidity corresponding to one crossing of the galactic disc relates to

New channel in high-energetic interactions:

e.g. Production of new heavy particle
or
Transformation of energy in gravitational energy
or
Interaction of primary with relic neutrino
or ...

A. Haungs ISMD 2003, Krakow – p.7/31
Origin of the knee ??

example: knee by reaching maximum of acceleration


two component supernova acceleration
- supernovae in interstellar medium
  ⇒ cutoff in the 100 TeV range
  ⇒ low energy protons

- supernovae into their own stellar wind
  ⇒ cutoff at $Z \cdot 10^{15}$ eV
  ⇒ source composition heavier
  ⇒ final cutoff at $Z \cdot 3 \cdot 10^{17}$ eV

$E_{\text{knee,A}} \propto Z \times E_{\text{knee,p}}$
Source of galactic cosmic rays: SNR’s ??

hints by: TeV $\gamma$-ray astronomy

H.J. Völk, 2003, highlight ICRC 2003, Tsukuba, Japan

TeV $\gamma$-production by inverse compton effect of electrons which produce also synchrotron emission.

at source electron and proton acceleration !?

TeV $\gamma$-production by $\pi^0$-decay.
Origin of the knee ??

example: knee by change of the efficiency of cosmic ray confinement in the Galaxy


Diffusion/drift model of cosmic rays inside the Galaxy
- constant source spectrum according to direct measurements at 1 TeV
- account for a regular magnetic field
- account for a random turbulent field

\[ E < Z \cdot E_{\text{knee,p}} \]
\[ \frac{dN}{dE} \propto E^{-\beta - 0.33} \]

\[ E > Z \cdot E_{\text{knee,p}} \]
\[ \frac{dN}{dE} \propto E^{-\beta - 1.0} \]

\[ E_{\text{knee,A}} \propto Z \times E_{\text{knee,p}} \]
Origin of the knee ??

example: Cosmic Ray particles transform energy in gravitational energy


Graviton production in pp collisions

- initial galactic and extragalactic components
- probability of graviton production
- free parameters: fundamental scale of gravity $M_f$ in $4 + \delta$ dimensions
- the graviton is unseen in air-shower
  $\Rightarrow$ to fit measured CR spectrum: $M_f = 8 \text{ TeV}$, $\delta = 4$

$E_{\text{knee},A} \propto A \times E_{\text{knee},p}$
Measuring extensive air showers

谴怨 3-fold problem:
E, A, interactions!

measure as much as possible redundant EAS informations!

multidetector system to get information from different EAS particle components!
KASCADE

KArlsruhe Shower Core and Array DEtector
KASCADE Array

- electron detectors
- muon detectors \( (E_\mu > 230 \text{ MeV}) \)
- muon tracking detector \( (E_\mu > 800 \text{ MeV}) \)

KASCADE Central Detector

- hadron calorimeter \( (E_h > 50 \text{ GeV}) \)
- trigger plane \( (E_\mu > 490 \text{ MeV}) \)
- muon chambers \( (E_\mu > 2400 \text{ MeV}) \)
High-Energetic Hadronic Interactions

The problem

- extrapolation of cross-sections to 'unknown' energies
- multiplicity of secondary particles in high-energetic interactions
- extrapolation in extreme forward direction
- diffractive part of cross-sections

⇒ see talk Ralph Engel
⇒ see talk Jens Milke

CORSIKA cross-sections

![Graph showing CORSIKA cross-sections with different models and data points.]

- Mielke et al.
- Yodh et al.
- Aglietta et al.
- Baltrusaitis et al. rescaled by Block et al.
- Block et al.
- Frichter et al.
- DPMJET II.55
- neXus 2
- QGSJET01
- SIBYLL 2.1

![Graph showing Rapidity (in p̅ - collisions) with data points and curves for different models.]

- Energy production
- Particle production

![Graph showing Multiplicity (in p̅ - collisions) with data points and curves for different models.]

- DPMJET 2.5
- neXus 2
- QGSJET01
- SIBYLL 2.1
- UA1/UA5

A. Haungs, ISMD 2003, Krakow – p.15/31
Energy and Mass Reconstruction

Measurement:
KASCADE Array data
900 days
0 – 18° zenith angle
0 – 91 m core distance
\( \lg N_e > 4.8 \)
\( \lg N^{tr}_\mu > 3.6 \)
\( \Rightarrow \) 685886 Events
Examples

Array

Electrons

Muons

Run 3226, File 2, leve 65041, Ymd 10215, Hms 225810, Neds 250, Npds 138
(Xc,Yc) = (-45.4,-51.0), (Ze,Phi) = (36.7,228.6), log10(Ne)=6.14, log10(Lmuo)=4.66
Unfolding Methods at KASCADE

searched:
\( E \) and \( A \) of the Cosmic Rays

given:
\( N_e \) and \( N^{tr}_\mu \) for each single event

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

with \( y = (N_e, N^{tr}_\mu) \) and \( x = (E, A) \)

Gold-Algorithm

\[
\frac{dJ}{d \lg N} = \sum \int \frac{dJ}{d \lg E} \cdot p_A(\lg N \mid \lg E) \cdot d \lg E
\]

with \( p_A \) by Monte-Carlo simulations.

With response matrix \( R_A \):

\[
y_i = \sum_{j=1}^{m} R^A_{ij} \cdot x^A_j
\]

\( \Rightarrow \) iterative minimization of \( \chi^2 \).

Bayesian-Approach

Monte-Carlo Simulations:
\[
P(y = (N_e, N^{tr}_\mu) \mid x = (E, A))
\]

Bayes-Theorem:

\[
P(x \mid y) = \frac{P(y \mid x) \cdot P_0(x)}{\sum_{i=1}^{m} P(y \mid x_i) \cdot P_0(x_i)}
\]

\( \Rightarrow \) iterative procedure to get spectra

Monte Carlo simulations using CORSIKA
with GHEISHA2002 and QGSJet2001 / SIBYLL 2.1
Results: Unfolding KASCADE Data

- knee caused by light elements
- $E_{\text{knee}}(A) \propto Z$ seems probable

but

- strong model dependence for the relative dependencies of the various mass groups
- both models do not describe the data distribution sufficient enough
Influence of Interaction Models

positions of maxima of $\lg N_e - \lg N_{\mu}^{tr}$ probability distribution

QGSJet

SIBYLL

position of $\chi^2$-contributions in the data plane
Sources of Uncertainties

- high-energy interaction models
- low-energy interaction models
- selection cuts?
- Monte-Carlo input
- unfolding procedures

Gold algorithm - QGSJet

Bayesian approach - QGSJet

- Knee caused by light elements
- $E_{knee}(A) \propto Z$ seems probable
Comparisons

all-particle energy spectrum

mean logarithmic mass

KASCADE preliminary

KASCADE preliminary

KASCADE (QGSJET;Bayes)

KASCADE (QGSJET;Gold)

KASCADE (SIBYLL;Gold)

KASCADE preliminary

Neural Net

Unfolding (QGSJET;Bayes)

Unfolding (QGSJET;Gold)

Unfolding (SIBYLL;Gold)

unf.-Gold;QGSJet

unf.-Gold;SIBYLL

unf.-Bayes;QGSJet

A. Haungs ISMD 2003, Krakow – p.21/31
Muon Density Measurements

**Muon Density Spectra**

Ratio of muon to electron number is mass sensitive:

\[ Y = \log(N'_\mu)/\log(N'_e) \]
\[ N'_\mu = f(N'_\mu', X_0, \lambda_\mu, \Theta) \]
\[ N'_e = f(N'_e, X_0, \lambda_e, \Theta) \]

\( X_0 \) = observation level,
\( \lambda \) = attenuation length

Knee caused by decreasing flux of the light elements!

---

Where is the proton knee?

different interpretations of the data
direct measurements (good proton identification, pure statistics)
TIBET experiment (163 events !, proton selection model dependent)
KASCADE experiment (good statistics, proton selection model dependent)

\[
\frac{dJ}{dE} \times E^{2.5} \text{ [eV}^{1.5} \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}]
\]

\[
10^{13} 10^{14} 10^{15} 10^{16} 10^{17}
\]

Primary Energy [eV]

\[
10^{15} 10^{16} 10^{17}
\]

\[
\text{conclusion not possible with the present precision of the measurements}
\]

A. Haungs ISMD 2003, Krakow – p.23/31
Direct measurements?

present situation of the knowledge:

⇐ conclusions not possible with the present uncertainties of the measurements

⇒ future: long flying balloons with larger sensitive areas (detectors of small weight)
**Origin of the knee ??**

**example: knee by different classes of Supernovae**


supernovae as source of cosmic rays
- different classes of supernovae
- different abundancies of the SN
  ⇒ cutoffs at different energies
  ⇒ source composition changes with energy

\[ E_{\text{knee},A} \propto Z \times E_{\text{knee},p} \]
\[ E_{\text{Knee}} \propto Z ? \]

...this seems to be a reasonable supposition!

by Acceleration (max Energie at SNR) ??
or by Transport (escape from Milky Way) ??

or a mixture of both effects ??

\[ \quad \leftarrow \text{conclusion not possible without knowledge of the 'right' interaction model!} \]
Anisotropy

$\approx 10^8$ events are analyzed to find anisotropies separately for all events, enriched light and heavy samples, and for $\gamma$ candidates (muon poor).

Large scale anisotropy:
Harmonic Analyses

$\rightarrow$ no anisotropy seen

Autocorrelation
of 1000 largest events

lines:
90\% confidence limit of $1 - P_{flu\text{c}}$
(level of sensitivity)

point source analysis:
$\rightarrow$ no point sources seen

G. Maier (KASCADE), 28th IC, 2003

A. Haungs ISMD 2003, Krakow – p.27/31
Gamma search

search for gamma induced EAS

- $N_{\mu}/N_e$-ratio
- slope parameter electrons
- smoothness of e-lateral distribution

![Graph showing Muon number vs Electron number and flux limits]

F.Fessler, G.Schatz (KASCADE), 27th ICRC 2003
Motivation for KASCADE-Grande

- Total flux
- Iron-Knee

Iron-Knee ?

$$E_{\text{knee}}(Z) \propto E_{\text{knee}}(H) \cdot Z$$

- Rigidity cut off for the iron?
- $$E_{k,\Phi} = 26 \times E_{k,p}$$

- KASCADE sensitive region
- Primary energy [GeV]
- Diff flux $$\frac{dJ}{dE} E^{2.5} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1.5}$$
Grande Array:

- 37 x 10m$^2$ scintillator stations
- Piccolo: 8 x 10m$^2$ trigger stations
- + original KASCADE

Detector areas:

- 965m$^2$ for e/$\gamma$
- 1070m$^2$ for $\mu$ (4 thresholds)
- 300m$^2$ for hadrons
KASCADE-Grande Collaboration

Institut für Kernphysik
Forschungszentrum and University of Karlsruhe
T. Antoni, W.D. Apel, F. Badea, K. Bekk, A. Bercuci, H. Blümer,
H. Bozdog, C. Büttner, K. Daumiller, P. Doll, R. Engel, J. Engler,
F. Feßler, H.J. Gils, A. Haungs, D. Heck, J.R. Hörandel, H.O. Klages,
G. Maier, H.-J. Mathes, H.J. Mayer, J. Milke, M. Müller, R. Obenland,
J. Oehlschlager, S. Ostapchenko, S. Plewnia, H. Rebel, M. Roth,

Universität Siegen
Experimentelle Teilchenphysik
M. Brüggemann, P. Buchholz, Y. Kolotaev, W. Walkowiak

Universität Wuppertal
Fachbereich Physik
R. Glasstetter, K-H. Kampert

IFSI, CNR
and University of Torino
M. Bertaina, A. Chiavassa, P. Ghia, C. Morello, G. Navarra, G. Trinchero, S. Valchierotti

Soltan Institute for Nuclear Studies, Lodz
A. Risse, J. Zabierowski

Yerevan Physics Institute
Yerevan, Armenia
A. Chilingarian, A. Vardanyan

Institute of Physics and Nuclear Ingeneering, Bucharest
I.M. Brancus, M. Petcu,

WWW-IK.FZK.DE/KASCADE_home.html
Summary (personal view)

- knee is caused by light primary elements
- composition becomes heavier above the knee
- knee position most probable varying with charge $Z$
- interaction models have to be further improved
- interaction models do not need "new" physics
- knee is by a mixture of acceleration, reacceleration, and diffusion effects
Summary (personal view)

- Knee is caused by light primary elements.
- Composition becomes heavier above the knee.
- Knee position is most probable, varying with charge $Z$.
- Interaction models do not need "new" physics.

Source of CR KNEE: A. Haungs ISMD 2003, Krakow – p.31/31